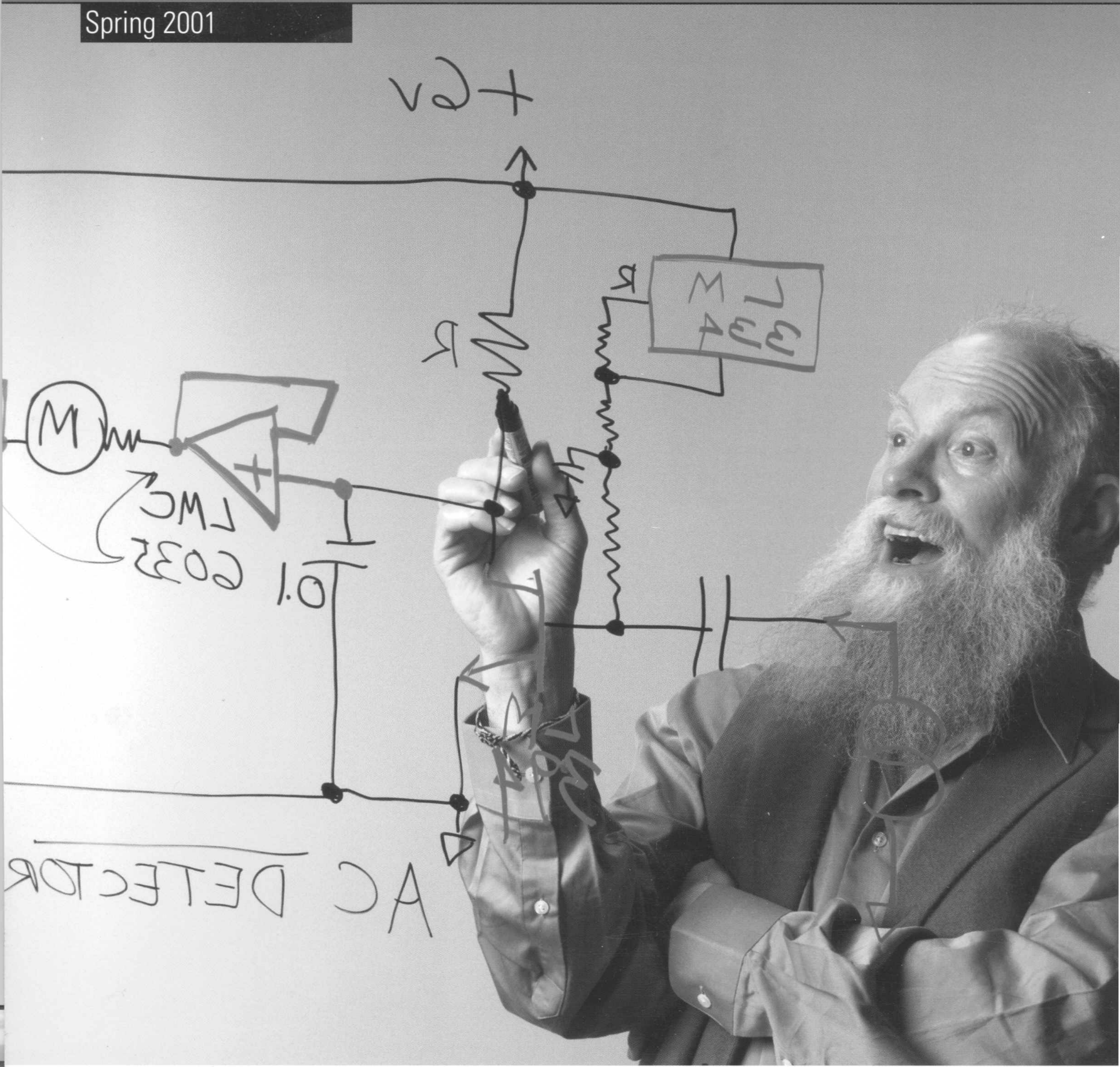
Analog Seminar Series - Supplement

Spring 2001



AL. REI KAGAN

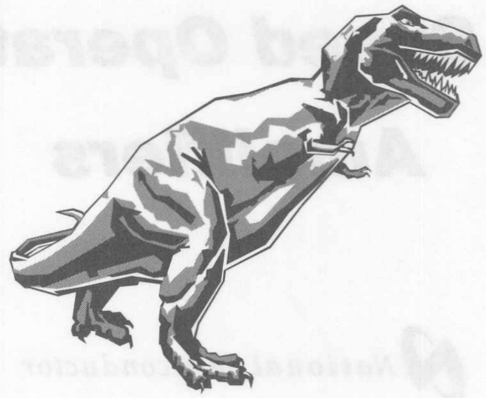
National Semiconductor

The Sight & Sound of Information

High Speed Operational Amplifiers

National Semiconductor

The Need for Speed



National Semiconductor

Analog Applications 2

You need a High Speed Op-Amp, so how do you choose one? Well, turning to the selector guide section of your favourite semiconductor vendor's catalogue is one way. That way you will find that one manufacturer's definition of High Speed can be subtly different from another one. An alternative is to go on-line and use a parametric search...but if the search is too tight, you risk eliminating suitable devices that may be more easily available and less expensive than the offerings turned up by your search. On the other hand, the sheer breadth of the Op-Amp sections in many catalogues means a wider search won't necessarily narrow the choice down far enough.

Unfortunately, in the past, semiconductor manufacturers have not been too helpful in making it easy to choose an Op-Amp. Although a new Op-Amp may have improved characteristics for particular applications, the data sheet is written in such a way as to widen the potential applications for the Op Amp, so the manufacturer can enjoy increased sales.

This situation is unlikely to change in the future. Some high volume applications have resulted in Op-Amps specifically targeted for those applications, but the manufacturer always remains alert to as yet unidentified opportunities.

Definitions & Parameters

Application Speed	100KHz to over 40MHz
Op-Amp GBW	10MHz to over 1GHz
f_{-3dB}	1MHz to over 400MHz
Small Signal	GBW, f_{-3dB}
Large Signal	Slew Rate, Settling Time
Differential Phase	0.05°
Differential Gain	0.05%

A further complication is that the way the user specifies the application does not necessarily match the way that the Op-Amp manufacturer specifies the Op-Amp. The user may think in terms of the maximum signal frequency involved and the amount of signal gain required (among other things), but for the Op Amp these two specifications are usually combined in a single parameter, the Gain BandWidth Product. While this reflects the universal nature of the Op-Amp, it also means that the impressive speed number on the front page of the data sheet diminishes rapidly in the real world application. For example, a 10MHz Op-Amp, used with a gain of 10, will have a -3dB corner frequency of 1MHz. For good signal fidelity (accurate gain and low distortion), the highest useable signal frequency is only 100KHz! Furthermore, at that signal frequency the maximum Op-Amp gain is only 100, a far cry from the impressive 100,000 to 1,000,000 probably quoted in the data sheet. To be fair, this situation exists because Op-Amps use global feedback, making the gain signal predictable and stable. On modern processes, amplifiers are built using local feedback, for significant gains at signal frequencies in the hundreds of megahertz range.

Sheer bandwidth is not the sole defining criterion for high speed, Op Amps are often used to process pulse waveforms where rise time and settling characteristics are important. In this connection, the terms "small signal performance" and "large signal performance" are not used to denote the actual size of the signal being processed, but to the differential input range over which the Op-Amp input stage remains linear. For "large signal operation" when the input differential signal is above a few millivolts, the output is slew limiting and the amplifier is open loop.

Other specifications seen on Op-Amps intended for video applications are "Differential Phase" and "Differential Gain". These help specify the small signal linearity of the Op-Amp.

Current Feedback

ALMOST UNLIMITED SLEW RATE

SIGNAL SOURCE IS CURRENT MODE

VERY LOW DISTORTION AT HIGH FREQUENCIES

National Semiconductor

Analog Applications 4

There is one constant factor present in the development of new Op-Amps, the desire for improved performance (or decreased manufacturing cost). For much of the past three decades this has been done by the adoption of new fabrication technologies, with small changes in design topology. An Op-Amp user from the late sixties would find the current generation of Op-Amps quite familiar. That is not to say there hasn't been a search for new, radical topologies, but the almost overwhelming pressure to produce Op-Amps that are optimised for ease of use by the non-specialist has meant that modern Op-Amps are quite similar to those of thirty years ago. They run faster, draw less current, use lower supply voltages, but are fundamentally unchanged.

There is one exception. In contrast to the basic voltage feedback (VFA) topology of most Op-Amps, there is the current feedback (CFA) topology, pioneered into commercial practice by Comlinear. National, as well as other manufacturers, has a large number of CFAs in its Op-Amp portfolio. Even so this exception was driven in a large measure by the development of new fabrication technologies allowing complementary transistors to be built on the same process and since conventional VFAs can also be built on the new processes, this does not ease the choice between similar performing Op-Amps.

In general terms, a CFA should be considered when:

1) An almost unlimited slew rate is a key consideration.

In ATE a CFA is often a good choice as a pin driver. Fast rise times are obtained by driving the input harder and increasing the current available for slewing the output.

2) The original signal is in a current mode form.

The amplifier is used as a transimpedance amplifier. Also inverting mode operation from matching sources can have improved Noise Figures over non-inverting configurations.

& VOLTAGE FEEDBACK

EASE OF USE

LOW SUPPLY CURRENT

LOW CURRENT NOISE

MULTIPLE SOURCES

3) Distortion caused by high frequency components of the signal (harmonics) must be kept as low as possible.

This is perhaps the real advantage of the CFA's closed loop frequency response over a VFA. For any value of closed loop gain the CFA will have more loop gain available at high frequencies than the VFA with a comparable bandwidth. The fact that the CFA bandwidth changes relatively little as the closed loop gain is raised is not as important as most proponents of CFAs would believe. If the compensation capacitor of a VFA is decreased as the closed loop gain is increased then it, too, could maintain the closed loop bandwidth.

A VFA should be considered when:

1) Ease of use is important.

There are hundreds of Op-Amps available with thousands of well tried applications. Because the inputs of a CFA are not inherently symmetrical, applications such as an integrator function are not practical. Compensation techniques are slightly different and the differences need to be understood.

2) Least power consumption for a given speed of operation is needed.

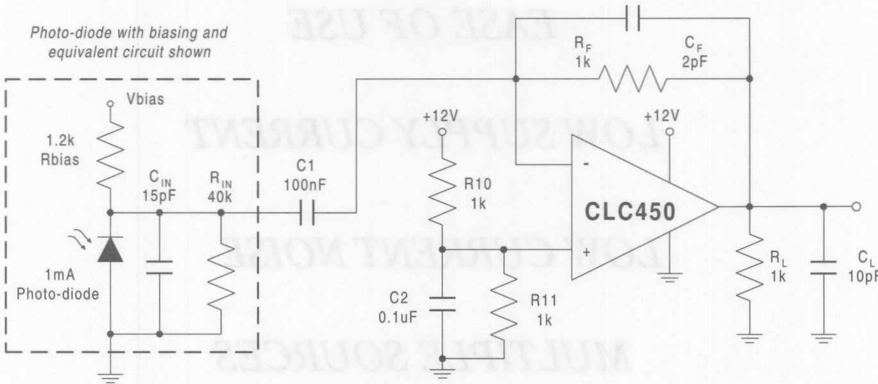
For comparable bandwidths, a VFA can be designed to draw less supply current. The distinction can often be blurry, but these are general considerations anyway.

2) Current noise can be significant to the application.

Comparable CFAs will have 10 to 100 times the current noise of the VFA.

(Voltage noise is more in favour of the CFA, all other things being equal, and can approach that of the simple differential pair. A VFA will usually have lower input stage transconductance and uses emitter degeneration resistors for stability purposes, and these resistors contribute to the input noise voltage).

CFA Photo-diode Amplifier



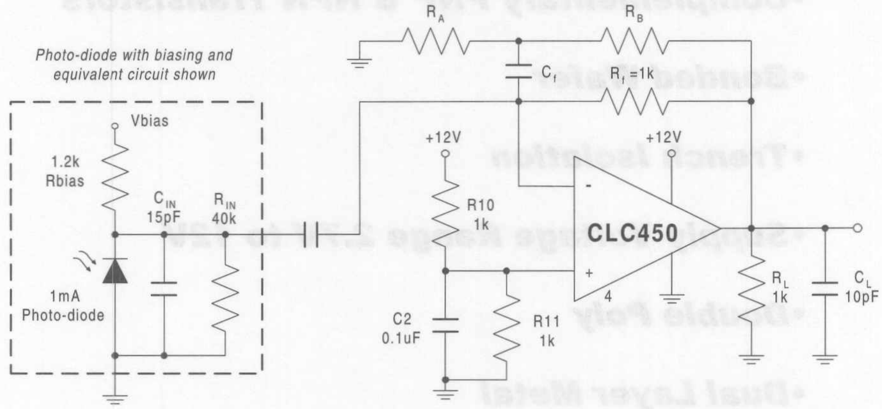
National Semiconductor

Analog Applications 6

A photo-diode amplifier is a good example of applying the strengths of the current feedback topology to the application. The input signal is a current and the required output is a voltage. Photo-diodes can present a significant capacitance at the input to the Op-Amp. The CFA has an effective internal buffer on the inverting node output impedance, producing a consequently low Ro, and the photo diode's output capacitance (Cin) introduces a zero in the Noise Gain at approximately 1/2πRoCin. Compare this zero to that of a Voltage Feedback op amp in a similar configuration [1/2π(Rin||Rf||Rbias)Cin] which tends to be much lower in frequency and more troublesome. This being the case, Cin has less of an effect on BW reduction and achieving stability is easier when using a CFA.

The example shown above is using the CLC450 (CFA). If Cin is sufficiently large, the closed loop phase shift will approach -180deg. at the cross-over frequency (where Open Loop Transimpedance Gain crosses the Noise Gain function). As with a VFA, the closed loop amplifier can be compensated by adding a small cap (Cf) across Rf. In this case, Cf was experimentally determined to be around 2pF for about 10% Overshoot in the Step Response. Cf improves stability by counter-acting the effect of the zero discussed in the paragraph above by introducing a low frequency pole (1/2πRfCf) and an inconsequential zero (1/2πRoCf).

Photo-diode compensation



National Semiconductor

Analog Applications 7

Sometimes the capacitor value required for the desired level of overshoot, whether determined by calculation or empirically, is too small to be practical, as in the previous example. It is possible to change the required 2pF compensation capacitor to a more reasonable value, by adding RA and RB as shown above (voltage divider).

The new value of Cf is given by

$$Cf = (1+R_B/R_A)Cf$$

This relationship holds true as long as R_B<<Rf, so selecting R_A=50Ω and R_B=500Ω

$$Cf = (1+500/50)2pF= \sim 22pF$$

which is a much more practical component value.

This value needs to be "fine tuned" in the real application for proper step response.

A New Process Technology VIP10™

- **Complementary PNP & NPN Transistors**
- **Bonded Wafer**
- **Trench Isolation**
- **Supply Voltage Range 2.7V to 12V**
- **Double Poly**
- **Dual Layer Metal**
- **Feature size down to 1 micron**

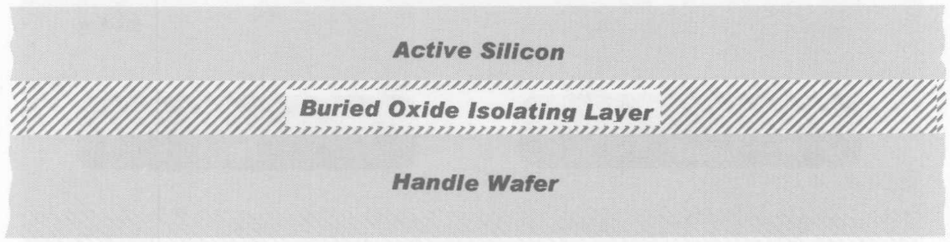
National Semiconductor

Analog Applications 8

Before looking at further applications of high speed Op-Amps, let us take a look at the fabrication technology that is involved. Up to today, National's high speed processes have been developments of the VIP process, one of the first production fabrication technologies to introduce low cost complementary NPN and PNP transistors on the same wafer. A high voltage, diffusion isolation process, VIP enabled the design of many successful Op-Amps. Now the focus is on lower supply voltages and, with battery powered equipment, less supply current for a given speed of operation.

To meet this demand, National is introducing a new process, VIP10™, which features low voltage operation, with high frequency NPN and PNP transistors that are able to maintain their performance at low supply voltages and relatively low current levels. The process uses bonded wafers with deep and shallow trench isolation to reduce parasitic capacitances and has dual layer metal to facilitate smaller die sizes. Simultaneously to announcing this new process, National is releasing several families of new high speed Op-Amps.

The Bonded Wafer



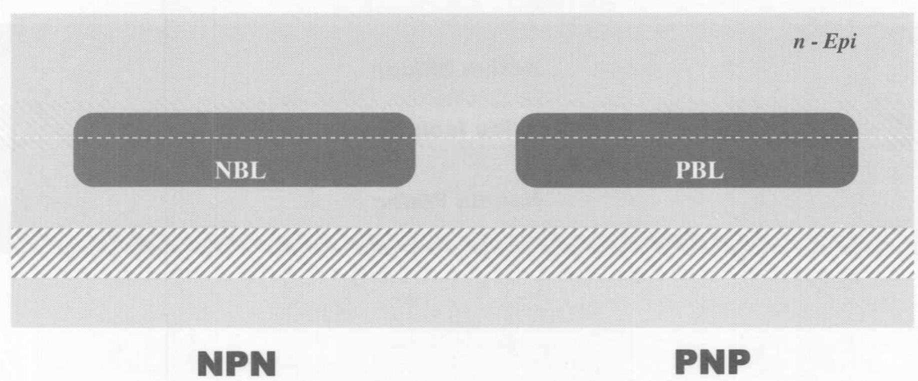
NOT TO SCALE

National Semiconductor

Analog Applications 9

The VIP10^{TM} process flow starts with a bonded wafer. The active silicon layer is bonded to the p type handle-layer with an isolating buried oxide layer. This buried oxide will allow transistor to transistor isolation and electrical isolation of the bottom of the wafer from the active silicon. When the finished product is attached to the die attach paddle (DAP) there is no electrical contact between the die and the paddle. This gives more flexibility in pcb layout for packages with an exposed DAP for heat sinking purposes. The heat sink copper can be floated at no electrical potential.

Buried Layers & Epitaxial Growth

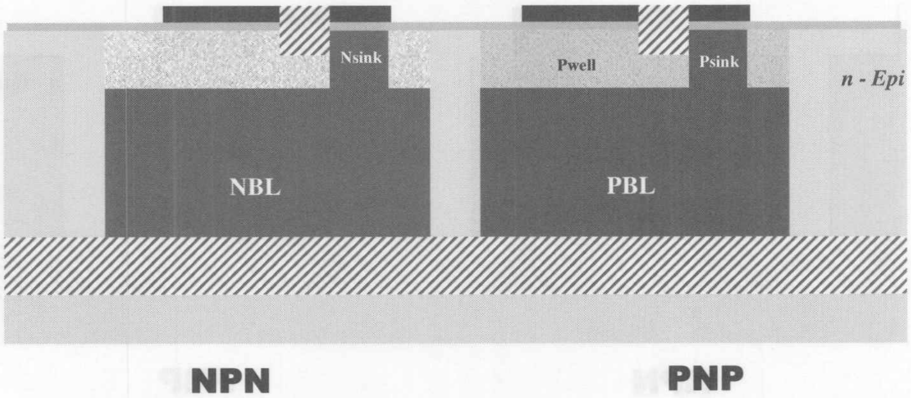


National Semiconductor

Analog Applications 10

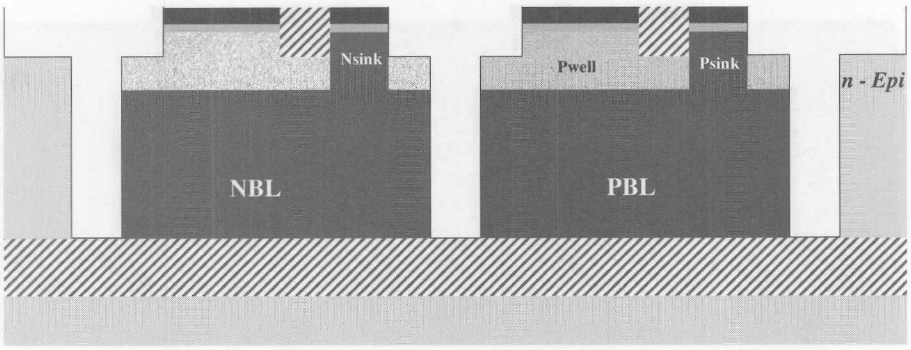
The first steps are to provide highly doped buried layers for low transistor collector resistance, and then epi is grown above these layers for the rest of the transistor structure, both NPN and PNP.

Wafer prior to Trench Isolation



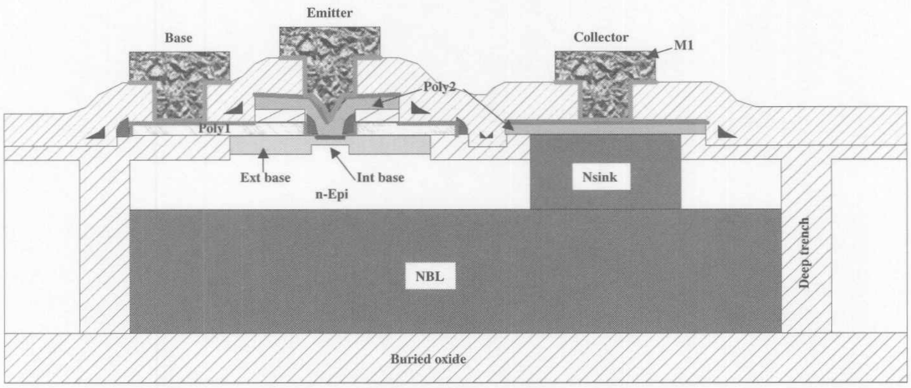
Several steps later, the wafer is ready for the trench mask with p-wells added for the PNP transistors and implants for sinkers to the buried layers of both NPN and PNP transistors.

Trench Plasma Etch



A deep trench is cut which reaches down to the buried oxide layer. A wider, shallow trench allows contact with the side walls of the base region.

Complete NPN Device



NPN Device

This is the completed NPN transistor. Note that the side walls and bottom of the collector region are in contact with oxide and not with a substrate, thereby eliminating junction to substrate diode capacitance. Similarly the oxide contacts the side walls of the base region. This means that the junction capacitances are of the order of tens of femto-Farads. Contrast this to a conventional diffusion process, where the substrate is the isolating material and the capacitance is that of a reversed biased diode. Not only is that capacitance much higher, hundreds of femto-Farads to as much as a pico-Farad for a power device, the capacitance changes with the bias voltage, increasing as the voltage goes down. The constant and low junction capacitance produced by the trench isolated process is well suited to low voltage, high speed designs.

The process uses double Poly, with Poly 1 defining the self aligned emitter window feature size of 1 um. While this may seem unimpressive compared to the modern high speed digital processes, it should be remembered that this process is designed for high speed analogue where the thinness of the intrinsic base region is an important contributor to high f_T. A better comparison is the diffusion depth, which is of the order of 100 Angstroms, or 0.1 um!

Transistor Parameters

NPN	PNP
f_T = 9GHz @ 5V	f_T = 8GHz @ 5V
f_T = 5GHz @ 1V	f_T = 3GHz @ 1V
β= 100	β= 60
V_A = 100V	V_A = 40V

National Semiconductor

Analog Applications 15

Here are a few of the salient transistor parameters. Note that the f_T is high, even at low supply voltages. A less commonly quoted parameter (not usually shown on the data sheets), is the Early Voltage. Along with β this reflects the collector output impedance of the transistors, with high βV_A values indicating high impedances. Since we use current sources as loads in gain stages, high gain is possible with fewer stages if the βV_A product is high. Another benefit is lower input offset voltages.

LMH™ New Op-Amps on VIP10™

3Volt Rail to Rail Output

- LMH6642 Single
- LMH6643 Dual

3dB Bandwidth	143MHz
Slew rate	120V/uS
THD @ 1MHz	-70dBc
THD @ 10MHz	-45dBc
Differential Gain	0.07%
Differential Phase	0.09°
Output Current	90mA
Supply Current	2.7mA/per amplifier

National Semiconductor

Analog Applications 16

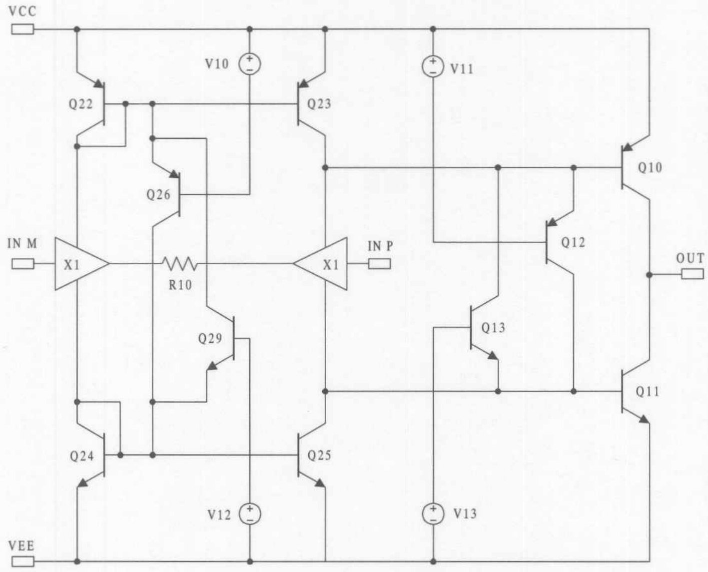
National is introducing the LMH™ series of high speed Operational Amplifiers on the new VIP10™ process. The LMH6642 (single) and LMH6643 (dual) are high speed Op-Amps designed to operate on supply voltages as low as 3V yet draw less than 3mA supply current. These are true single supply Op-Amps with an input common mode range that extends from -0.5V below ground to within 1V of the positive supply rail. At the output with a 2KΩ load, the signal swing can come within 40mV of the rails, increasing to only 160mV with 150Ω loads. The noise voltage is a respectable 16nV√Hz and the outputs can deliver 90mA and a slew rate of 120V/uS. This combination of parameters, along with low Differential Phase and Gain, are very suitable for professional grade video applications.

LMH6642/43 Output Stage

Analog Applications 18

Although similar to the classical common emitter Class AB output stage used in many Op-Amps, the LMH6642/43 family uses a common collector output stage. This means that the output voltage can swing as close to the supply rails as the collector to emitter saturation voltage of the output transistors. For light loads this is only a few millivolts.

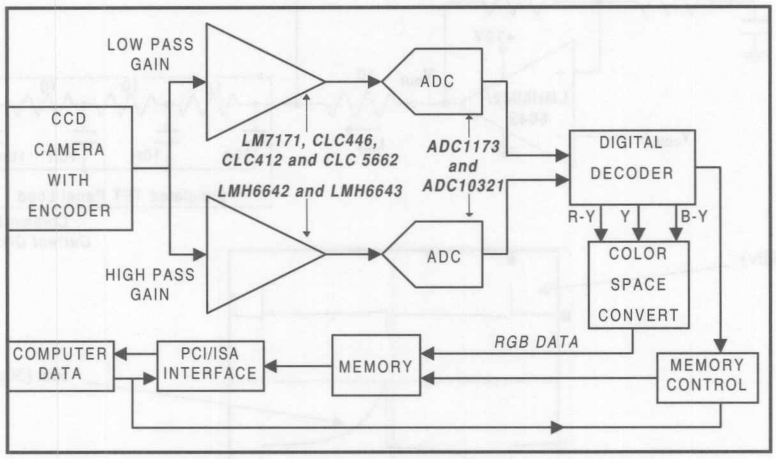
LMH6642/43 Output Stage



National Semiconductor

Although similar to the classical common emitter Class AB output stage used in many Op-Amps, the LMH6642/43 family uses a common collector output stage. This means that the output voltage can swing as close to the supply rails as the collector to emitter saturation voltage of the output transistors. For light loads this is only a few millivolts.

Video Applications

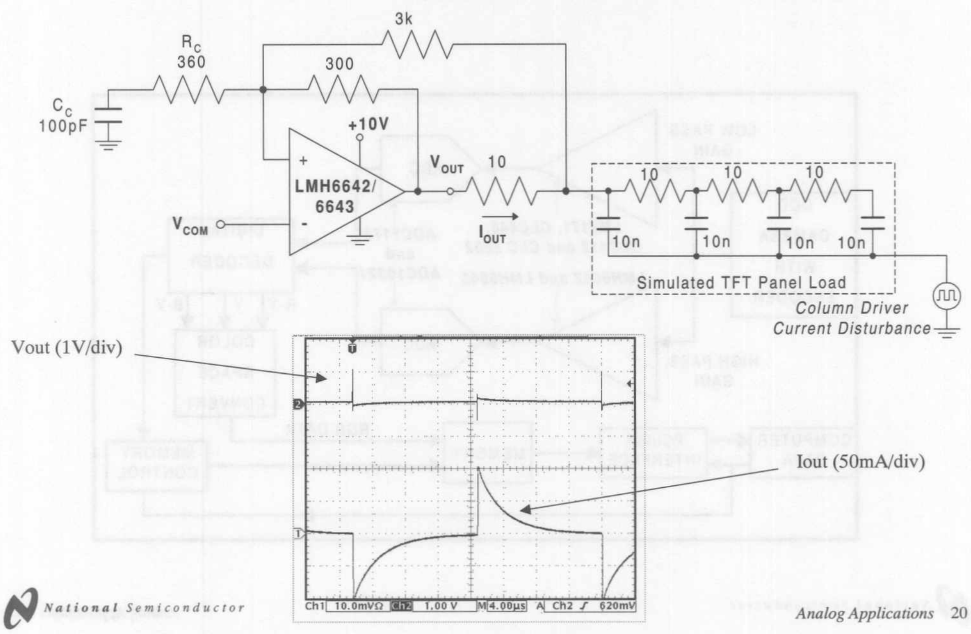


Apart from the more obvious Op-Amp applications as video buffers for cable drivers, high speed Op-Amps can be used in camera systems (and scanners) to buffer the signal from the CCD into the D/A converter.

Useful devices for both luminance and chrominance channels are the LMH6642 and LMH6643 which draw only 2.7mA supply current, yet are able to deliver 90mA load currents. Other suitable devices are the LM7171, CLC446, CLC412 and the CLC5602. Differential Gain and Phase numbers can be as low as 0.02% and 0.02° respectively for the CLC446. These specifications are arrived at by applying a small high frequency signal to the amplifier (3.58MHz or 4.43MHz) and varying the dc level of this waveform through the entire common mode input range. Any deviations in amplitude or phase of the waveform at the amplifier output are recorded, with the maximum deviation resulting in the DG/DP numbers for the amplifier.

In this application, the amplifiers are driving the ADC1173, 8 bit, or ADC10321, 10 bit converters. Both these converters offer at least 3dB better S/N than competitive devices in the 8-10bit category.

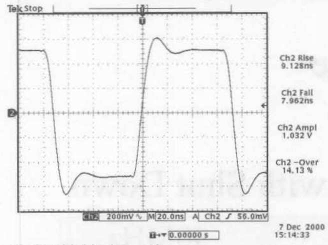
Driving TFT Panel V_{COM}



An application which uses an Op Amp and requires high output current is the V_{com} driver used in TFT LCD panels. The schematic shown above depicts this application using the LMH6642/ 6643 family in a simulated environment in order to investigate how the Op Amp behaves under dynamic conditions.

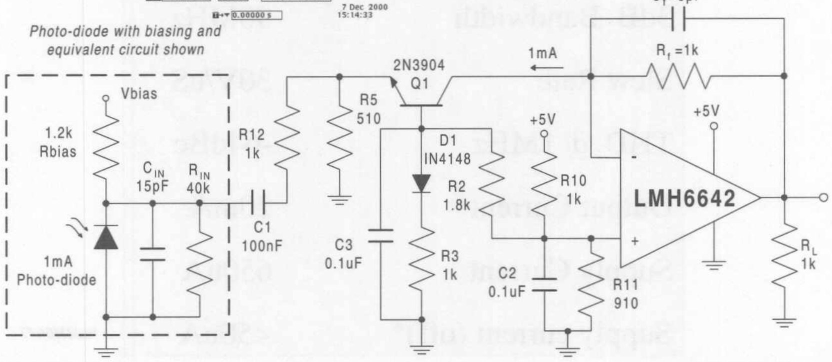
As can be seen above, the Op Amp is configured for unity gain configuration. Its output is connected to the V_{com} pin of a TFT panel and its function is to maintain the V_{com} voltage under dynamic output current load. The TFT panel is mostly a capacitive load (depicted by the simulated load shown). The components in the simulated load vary from panel to panel and increase in capacitance with larger panels. Inside a TFT panel, the Column driver drives the TFT elements while the Op Amp tries to maintain the V_{com} voltage. Because of the capacitive nature of the load, care must be given to the selection of the Op Amp and its application. Here, with the component values shown, it is necessary to use Rc and Cc in order to ensure the stability of the Op Amp with this load. In this example, Iout reaches +/-100mA as a result of the Column Driver action. Vout waveform shows the Op Amp output voltage under this output current. Under ideal conditions, the Op Amp will have minimum Vout shift due to Iout. However, in a practical application, Vout is allowed to show some modulation as long as its recovery time is a small percentage of the overall time.

Photo-diode Amplifier
(single supply, low voltage application)



Output Step Response

20nS/div, 0.2V/div.



National Semiconductor

Analog Applications 21

The new LMH6642, High Speed, low voltage voltage feedback Op Amp can be used as the Transimpedance gain block as show above. This device can operate down to 2.7V single supply and its -3dB BW(Av=+1) is more than 100MHz (Is=2.7mA)! Because of the "Dielectric Isolation" process this device is based on, the traditional supply voltage vs. speed trade-off has been alleviated to a great extent allowing low power consumption and operation at lower supply voltages. In addition, the device has Rail-to-Rail output swing capability to maximize the output swing and is capable of driving +/-50mA into the load.

With 5V single supply, the device input/ output is shifted to near half supply using voltage dividers from Vcc. The Common Base transistor stage isolates the Photo diode's capacitance from the inverting terminal allowing larger BW and easing the compensation required. Note that Q1 Collector does not have any voltage swing and the Miller effect is minimized.The diode on Q1 base is for temperature compensation of its bias point. Q1 bias current was set to be large enough to handle the peak-to-peak Photo diode excitation and not too large as to shift U1 output too far from mid-supply.The overall circuit draws about 4.5mA from the +5V power supply and achieves about 40MHz of closed loop BW @1Vpp.

LMH™ New Op Amps on VIP10™
2.7V Rail to Rail I/O

- **LMH6645** Single
- **LMH6646** Dual
- **LMH6647** Dual with Shut Down

3dB Bandwidth	90MHz
Slew Rate	30V/uS
THD @ 1MHz	-64dBc
Output Current	20mA
Supply Current	650uA
Supply current (off)*	<50uA

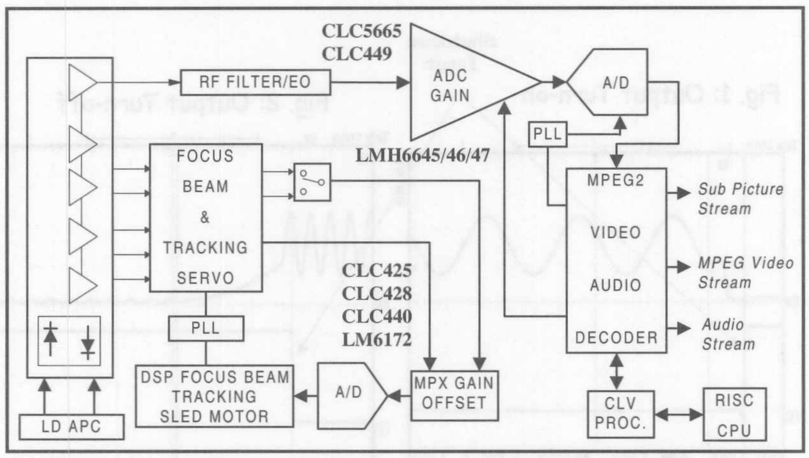
**LMH6647*

National Semiconductor

Analog Applications 22

With a more modest speed of 90MHz and a slew rate of 30V/uS, the LMH6645/6/7 family can operate on supply voltages as low as 2.7V and draw only 650uA of supply current. Noise voltage is similar to that of the LMH6642/3 family at 15nV√Hz. The LMH6647 single has the same characteristics as the other members of this family and includes a shutdown feature which reduces the supply current in shutdown to less than 50uA. Turn on and turn off times for this part are less than 50nSecs.

High Speed, High Resolution



National Semiconductor

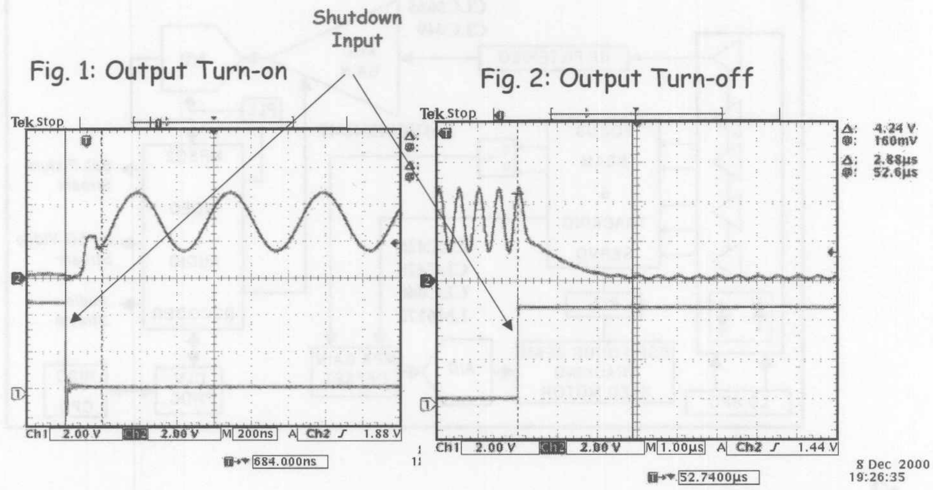
Analog Applications 23

The low quiescent supply current makes these devices useful where overall power consumption is important, but speed is still required. The LMH6645/46/47 Op-Amps are used to drive high speed converters, again 8 to 10 bits at up to 20MSPS, and in the 12 to 14 bit range for motor control purposes with update rates from 2.5MHz to 10MHz.

If higher power consumption can be tolerated then the CLC5665 can maintain a gain flatness of 0.1dB over a 20MHz frequency range with a slew rate of 1200V/us. The CLC449 has an even higher slew rate of 2500V/us. For motor control the servo speed CLC425,428, 440 and LM6172 are appropriate.

LMH6647: High Speed Op Amp with "TRUE" shutdown

(ideal for saving power and multiplexing)



National Semiconductor

Analog Applications 24

A device which allows itself to be turned off when not in use can find particular application in battery powered portables. There are many such devices available from a variety of manufacturers. However, High Speed devices traditionally do NOT allow turning the device off when not in use to save power. The major use for their "power-down" state is to put the output in a "Hi Z" condition (similar to Tri-stating in logic). In this manner, it would be possible to multiplex many devices on one line.

The LMH6647 with its low voltage operation (Vs=2.7V), low supply current (650uA), rail-to-rail input and output and high speed (80MHz for -3dB BW) operation, is versatile enough to allow "true" device shutdown. In this mode of operation, the supply current drops to below 10uA allowing significant power savings. LMH6647's output stage is designed to deliver +/-20mA, making it suitable for a variety of loads.

The scope photos above, show the typical turn-on and turn-off characteristics while amplifying a 2MHz sine wave. Here the device is operated from a single supply of 5V (Av=+2, Rsource=10K, RL=10K to ground). As can be seen, the output is "valid" in about 200ns. During turn-off, with the output load resistance of 10K, it takes around 3.2us for the output to settle to 0V.

LMH™ New Op-Amps on VIP10™

Low Noise High Speed Op-Amps

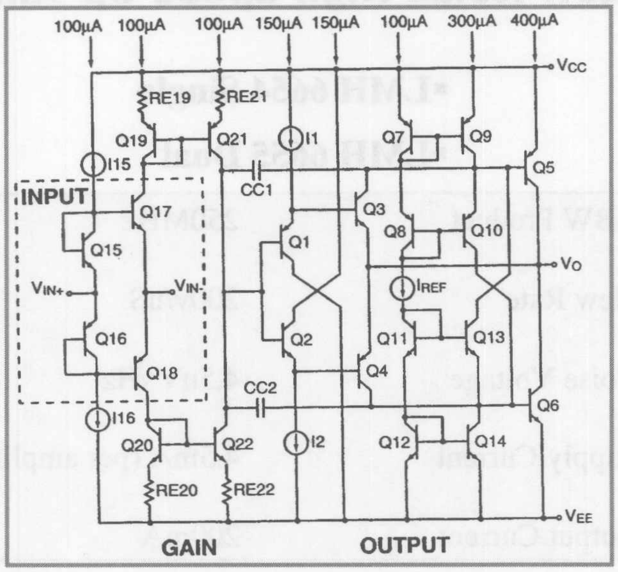
- LMH 6654 Single
- LMH 6655 Dual

GBW Product	250MHz
Slew Rate	200v/uS
Noise Voltage	4.5nV√Hz
Supply Current	4.5mA (per amplifier)
Output Current	200mA

National Semiconductor

Where noise voltage is important, the LMH6654/5 family are high speed, low noise Op-Amps with a typical input referred noise voltage of 4.5nV√Hz. A supply current of 4.5mA per amplifier ensures a GBW of 250MHz with a slew rate of 200V/uS. In addition the output stage can deliver 200mA to the load.

Low Quiescent Power Stage Delivers High Current/Voltage Output Swings



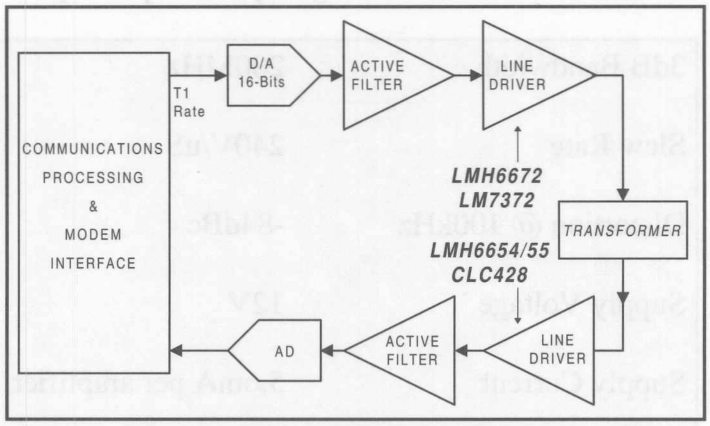
National Semiconductor

Analog Applications 26

In order to deliver very high output currents at low distortion, yet not draw correspondingly high quiescent supply currents, the output stage topology of the LMH6654/55 is similar to that of the CLC450, shown here.

Traditionally, amplifier output stage topologies have been a compromise between having a good output swing (relative to the supplies) and being capable of delivering reasonable amount of current to the load. A new patented design approach allows output swings to within 1V of either rail while delivering in excess of 100mA (sourcing and sinking), with a quiescent current budget of only 0.8mA! For a positive going signal presented to Vin, the current through Q3 increases while current through Q4 decreases. This increase in Q3 current, simultaneously increases Q5 current and reduces Q4 & Q6 current (through the Q10 path) thereby increasing the net current delivered to the load. When the output current is larger than the quiescent current of Q5, Q6 (400uA), the circuit operates as a class AB stage; that is, when the output is sourced, Q5 is the dominant active output device while Q6 becomes the dominant active device as output current is sunk.The net effect of all this is that significant load current can be sourced/ sunk and the power consumption and voltage swing are not sacrificed to achieve this.

Communications



National Semiconductor

Analog Applications 27

For the increasingly popular xDSL systems, high speed Op Amps are used to drive the upstream signal through the copper wires, and to amplify and buffer the down stream signal to the modem. Although high speed is necessary, despite relatively low data rates, other parameters are important.

On the receiver side, low noise is important to maximise the dynamic range, and the LMH6654 and LMH6655 feature an input referred noise voltage of 4.5nV√Hz. The wide gain bandwidth of 250 MHz means significant gain can be used for the 1MHz down stream signal. For even lower noise, CLC425, 428 and CLC440 have input referred noise voltages as low as 2nV√Hz. As a dual the CLC428 is well suited for the differential receiver function and offers very tight matching between the two amplifiers. The LM6172, also a VFA dual, has the same high GBW (100MHz) and a slew rate of 3000V/us.

On the transmit side, high output current and voltage swing capability is important in addition to low distortion. The LM7171 single has a GBW over 200MHz and is able to deliver 100mA signal currents into 100Ω loads. The newly introduced LM7372 is a dual version that can deliver even more load current, 150mA, at similarly low distortion levels. Both these devices can operate from 30V supplies.

For supply voltages at the 12V level the LMH6672 is more suitable.

LMH™ New Op-Amps on VIP10™

▪LMH6672 *Dual High Speed Op-Amp*

3dB Bandwidth	200MHz
Slew Rate	240V/uS
Distortion @ 100kHz	-84dBc
Supply Voltage `	12V
Supply Current	5.6mA per amplifier
Noise Voltage	4nV√Hz

National Semiconductor

Analog Applications 28

The LMH6672 has a GBW product of 250MHz. The output voltage swing is much higher than for the LMH6654/55 series, the LMH6672 delivering 200mA with a 10V(p-p) swing on a 12Volt supply.

Differential Line Driving

HIGH SPEED/LOW DISTORTION

BRIDGE AMPLIFIERS

POWER DISSIPATION

PACKAGING/HEATSINKING

The xDSL modem application is worth studying in greater detail, since it combines many elements of a high speed Op-Amp application that need to be addressed, other than selecting an Op-Amp that "just seems fast enough".

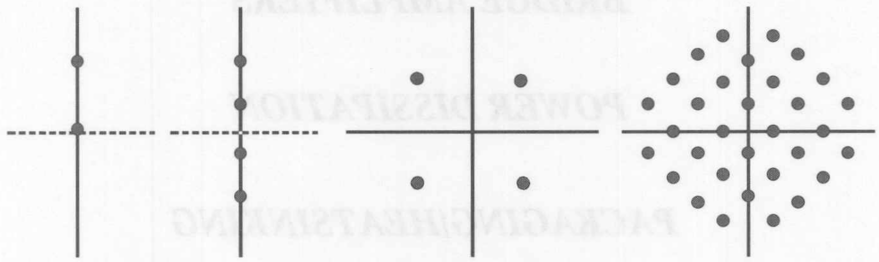
Although the transmit highest frequency is no more than 100KHz at the CPE (Customer Premise End) modem, and barely over 1MHz at the CO (Central Office) end, Op-Amps that are suitable for line driving will have GBWs in excess of 80MHz. The differential character of the twisted copper pair requires two amplifiers connected in a "bridged" mode, so that output voltage swings are substantially larger than the supply voltage available to the modem. The delivered power is only 20mW, but the internal power dissipated by the Op-Amp can be a factor of 25 or more times higher, requiring the circuit designer to consider different topologies to help minimise this power dissipation. The modern trend to packages with ever smaller footprints exacerbates the heat dissipation problem, since many surface mount packages are not amenable to effective heatsinking.

The following pages will examine an application specific example for xDSL, but because the design conflicts are common to many high speed designs, hopefully this will show directions that can be taken to provide solutions to a wide variety of designs.

xDSL

x Digital Subscriber Loop/Line

x = A Asymmetric DSL
= S Symmetric DSL
= V Very High Bit Rate DSL
= RA Rate Adaptive DSL
= H High Speed DSL



BINARY 2BIQ 4 Level QAM 32 Level QAM

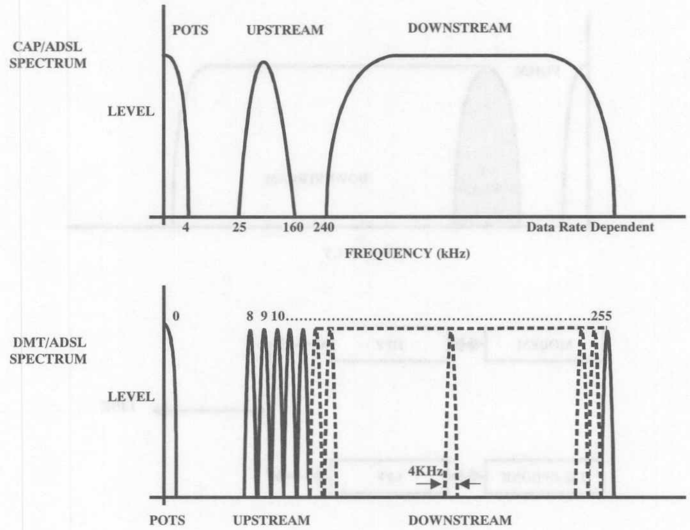
National Semiconductor

Analog Applications 30

Other than forcing the circuit designer to become familiar with a whole new set of acronyms, xDSL (standing for Digital Subscriber Loop/Line, with the x representing the various flavours of DSL) enables broadband communication into small businesses and residences via the the twisted copper pair that provides the traditional voice telephone service or POTS (Plain Old Telephone Service). Originally conceived in the early nineties as a means for providing VOD (Video On Demand) in competition with cable providers, the explosive growth of the Internet in the late nineties has resurrected DSL as a viable means to transmit and receive digital data through existing phone lines.

The impedance/frequency characteristics of the twisted copper pair means that some form of data compression is required in order to reach acceptable data rates. Most of these modulation schemes are based on a variation of QAM (Quadrature Amplitude Modulation). Instead of simple binary (a string of ones and zeros), a carrier is modulated in amplitude and phase. With a single carrier phase, modulating the amplitude by two levels doubles the transmission efficiency, 2B1Q. This is the basic modulation scheme used in DSL. Using more carrier phases and amplitudes produces more complex constellations for even higher data rates, at the risk of more susceptibility to interference.

ADSL with CAP & DMT



National Semiconductor

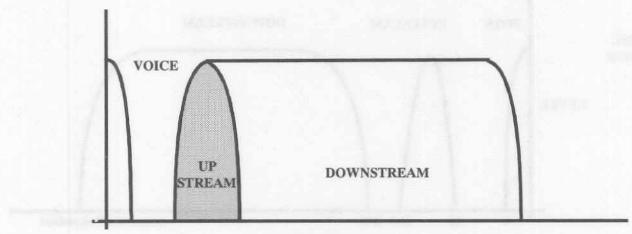
Analog Applications 31

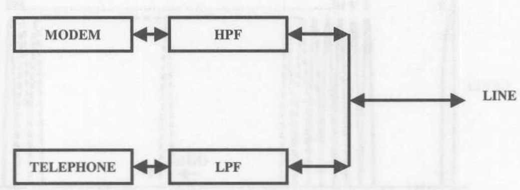
The spectrum of ADSL with CAP is shown above. For the downstream data channel two carriers at the same frequency but with a 90° phase difference, well above the voice baseband signal, are each modulated with a number of levels. The bandwidth occupied by this signal depends on the number of levels used (between 4 and 512) giving data rates of around 1.5MHz on long loops to as much as 8MHz on short loops. A similar modulation scheme is used for the upstream carrier but with a lesser number of levels being used for an occupied bandwidth between 25KHz and 160KHz. Because the impedance/frequency characteristic of the copper pair is so variable, CAP uses adaptive equalisation. At startup there is a 'training' phase to identify the individual line characteristic. Since this equalisation is over a 50dB dynamic range, extensive number crunching is needed.

ADSL with DMT takes a slightly different approach. Instead of single carrier frequencies, DMT divides up the available spectrum into 256 subchannels, each 4KHz wide. The space for the 8 lowest subchannels is left open for the POTS system, as with CAP. The remaining subchannels can each be modulated with up to 15 bits of data so high data rates are achieved by using more subchannels. Depending on the system, the lower 32 of the occupied subchannels are used by both the downstream and upstream signals, with echo cancellation separating the signals in the area of overlap. Other systems sacrifice a little of the downstream rate by reserving the lower subchannels for the upstream signal exclusively.

The assumption with DMT is that the line characteristic will not change much in a narrow 4KHz bandwidth and adaptive equalisation is not needed. Nevertheless, the extensive Fourier transform calculations to reconstruct the signal from the useable subchannels involves an equal amount of number crunching.

ADSL & NEXT



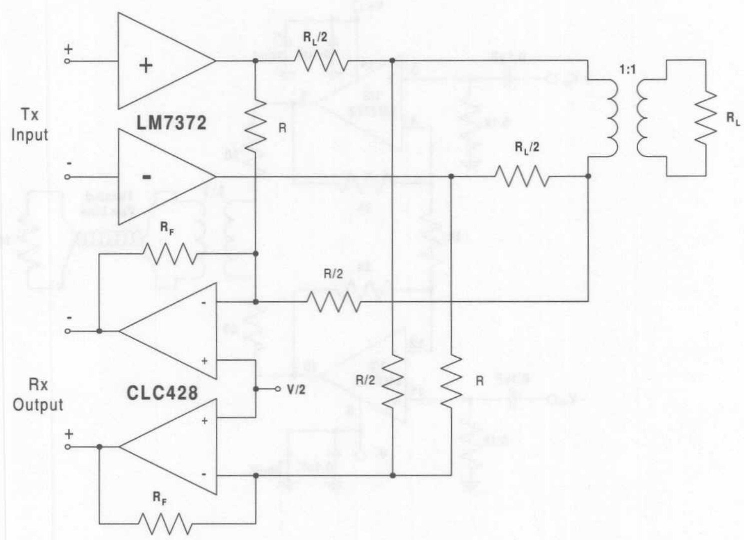


As the title ASDL says, the bandwidth allocated to the downstream and upstream channels is asymmetric. For most residential applications the slower upstream data rate is considered acceptable since it is anticipated that the amount of download will always be much larger than the upload from the CPE. More importantly, this asymmetric arrangement helps to minimise the effects of Near End Cross Talk, or NEXT. A large number of copper pairs are bundled into each telephone cable, and if the same bandwidth was occupied for both upstream and downstream transmissions, then an adjacent strong upstream transmission could easily interfere with the much weaker downstream transmission, particularly as the distance from the CO increases.

Installation of the CPE modem is not as easy as most people would want. Many installations require a splitter to separate the voice/fax/analogue modem traffic from the DSL modem traffic and vice versa. The high pass filter protects the modem from the POTS, but also helps to prevent low frequency side lobes from the modulation process increasing the noise floor in the voice channel. Similarly the low pass filter protects the POTS channel from the 30KHz and up signals from the DSL modem, and simultaneously shields the modem from the many non-linear impedances that are present on the POTS line.

Splitter-less DSL (G-Lite for example) eliminate one of the filters, the low pass, by reducing the transmit power of the DSL modem by 75% so that, in the absence of the LPF, interference to the POTS channel is kept at acceptable levels.

The ADSL Transceiver



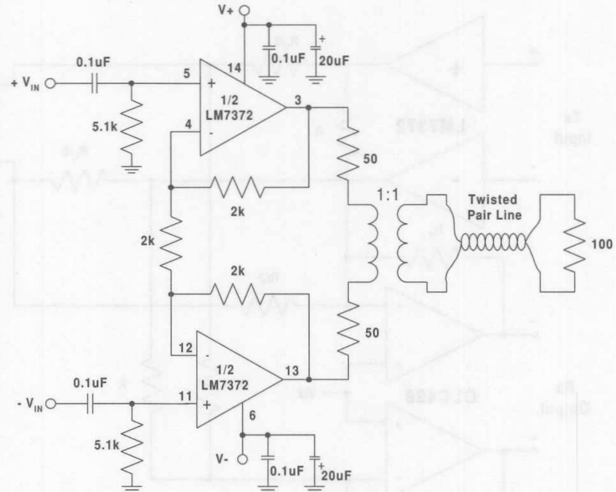
National Semiconductor

Analog Applications 33

A typical ADSL transceiver will look as shown here in this simplified schematic. Note that the output of each transmitter Op-Amp drives a terminating resistor to match the line impedance of 100Ω. With a 1:1 transformer turns ratio these terminating resistors will be 50Ω each. As we will see later, this arrangement requires a high voltage Op-Amp such as the LM7372. When low supply voltages are used, a step up transformer is required to get the necessary signal swing on the line. A 1:2 turns ratio will decrease the size of the load resistors correspondingly, requiring higher load currents. The LMH6672 was designed with this in mind, and can deliver over 200mA.

The receiver Op-Amps are used in an inverting gain mode so that with the resistor ratios shown, there will be a first order cancellation of the transmitter signal at the receiver inputs. If a different transformer turns ratio is used, particularly with lower supply voltages, in order to obtain sufficient transmitter voltage swing on the line, the resistor ratios will change correspondingly. While stepping up the output swing with a higher turns ratio makes it easier for the transmitter, it does mean that the received signal will be attenuated by a like amount.

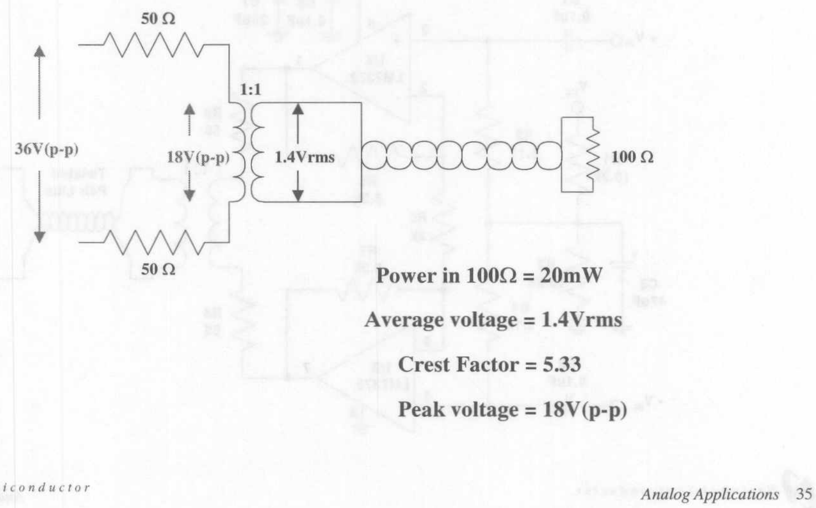
LM7372 Differential Transmitter



National Semiconductor

Here is a more detailed view of the transmitter section, using the high speed, high supply voltage dual LM7372 Op-Amp. This is a differential input to differential output topology, with a split 24V supply voltage. While a split supply avoids the need for input bias networks, there are other consequences to using split supplies, particularly with regard to heatsinking, which we will cover later. The LM7372 is stable with non-inverting gains as low as +2 as shown here. This gives the widest bandwidth and lowest distortion but higher gains are generally used (between 5X and 8X, to get sufficient output swing to meet the DSL drive specification. On the other hand, having more signal gain than necessary is not recommended, since higher gains will reduce the available loop bandwidth at high frequencies. A good rule of thumb is to keep the closed loop bandwidth close to 10X the highest signal frequency. The pin numbers given are for the LM7372 in a SOIC 16 package.

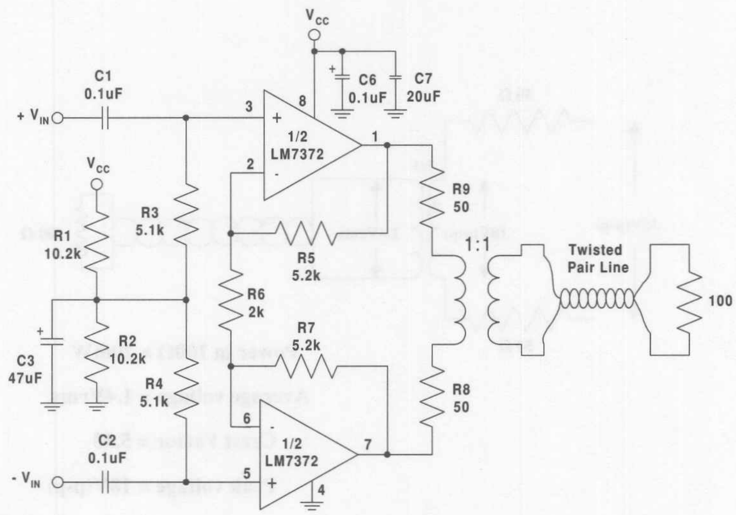
Power and Swing for DMT



At first sight the output swing and power requirements for the DMT modulated DSL signal appear to be very modest. At the CPE end, the transmitter must put an average power of 13dBm onto the copper pair which is assumed to have a characteristic impedance of 100Ω. This translates to 20mW on the line. Since each amplifier has to drive the terminating resistor as well as the load, then each amplifier will have to deliver 20mW for a total of 40mW. The average output voltage swing is 1.4V, or 4V(p-p) which is well within the capability of an Op-Amp running on a 12V supply.

Unfortunately, in the real world, things are not as simple. The specification is for the average power delivered to the load. A DMT modulation uses a large number of frequencies to transmit high data rates, and at any time the phase and amplitude of the individual tones will be such as to generate a combined signal amplitude with a higher instantaneous or peak value than 4V(p-p). For DMT the crest factor is assumed to be around 5.33, for a peak value of 15V(p-p). Add to this a little headroom for transformer losses (0.5-1.0dB) and the voltage drop across the terminating resistors, the transmitter output must be capable of swinging up to 36V(p-p). This looks to be far more than an Op-Amp can handle, even with a 30V supply.

Single Supply Differential Drive



National Semiconductor

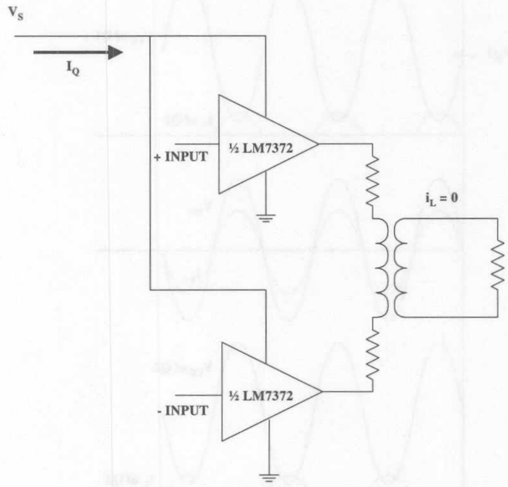
Analog Applications 36

This is where differential or bridge drive enters the picture. By using two amplifiers to process the input signal, but with one input reversed in phase from the other, as one amplifier swings positive by 18V the other swings negative by 18V. The net result is a load swing of 36V even though the amplifiers are operating with a supply voltage sufficient to support an 18V swing. A 24V supply ensures adequate headroom for peak signal swings with low distortion. The bias network of R1 and R2 places the dc voltage of the non inverting inputs at +12V. The pin numbers are for an LM7372 in the LLP-8 package.

As noted earlier, larger signal swings are possible by increasing the transformer turns ratio.

For a 12V supply, a 1:2 turns ratio will give the necessary load swing, but now the peak current from each Op-Amp is doubled.

Power Dissipation



$I_Q = 13mA$

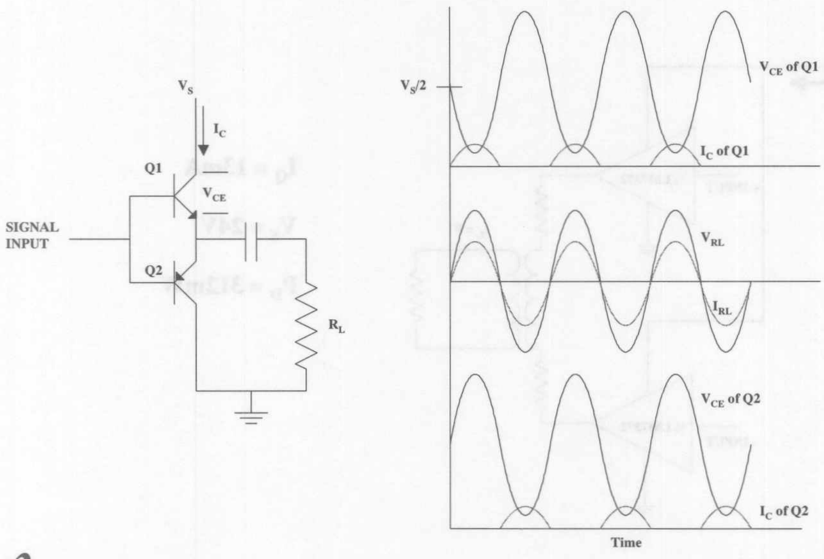
$V_S = 24V$

$P_D = 312mW$

For many Op-Amp applications, power dissipation is not very often an issue. For high speed applications it is. Generally an Op-Amp designed for good performance at high frequencies will have bias currents of several milliamps. At low supply voltages with light loads, the power dissipation can be low, but as the signal swing goes up, requiring higher supply voltages, and the load impedance decreases to the order of 100Ω or less, then the power dissipation can be a significant factor in the design. Power dissipation has several impacts other than requiring larger power supplies. If a lot of the circuits in an enclosure are dissipating heat (a DSLM for example), then the temperature within the enclosure may be driven higher than acceptable. Ventilation or forced cooling can be necessary at high ambient temperatures. For the individual I/C within the enclosure, this temperature rise, coupled with the higher junction temperature caused by internal power dissipation, may take the device out of the range specified by the I/C manufacturer, degrading performance and reducing reliability.

There are two major components of power dissipation that contribute to the Op-Amp's internal junction temperature. The first is the quiescent supply current which is present when no power is being delivered to the load. Usually for a given supply voltage, this component of power can easily be calculated from the data sheet parameters for the I/C, even at elevated ambient temperatures. For the LM7372, the quiescent supply current is listed as 13mA (using both amplifiers). With a 24V supply, therefore, the quiescent power dissipation is 312mW. At elevated temperatures the worst case dissipation will be higher, but for the moment we will stay with this number.

Class B Waveforms



National Semiconductor

Analog Applications 38

The second component, that of additional power dissipated within the I/C while delivering power to the load, is not so easily calculated, and empirical measurements may be necessary.

The majority of Op-Amps use a form of the Class B output stage topology, and this is where the power is dissipated when the amplifier is driving the load. Dissipation in either transistor is the product of the collector to emitter voltage and current. For one half of the load cycle Q1 is conducting, for the other half Q2 is conducting. Notice that in either case, during conduction as the collector to emitter current goes up, there is a corresponding fall in the collector emitter voltage. This means that during the early part of conduction, power dissipation will increase with load current, but as the collector emitter voltage approaches zero, the power dissipation will go down again.

Calculating the Power Dissipation

$V_{CE} = V_S - (V_S/2 + V_L\sin\omega t) = V_S/2 - V_L\sin\omega t$

$I_{EC} = V_L\sin\omega t/R_L$

$p_D = (V_S/2 - V_L\sin\omega t) \times V_L\sin\omega t/R_L$

$P_D = (1/2\pi)\int_0^{\pi}(V_S/2 - V_L\sin\omega t)(V_L\sin\omega t/R_L)d(\omega t)$

$P_D = (1/\pi)\int_0^{\pi}(V_S/2 - V_L\sin\omega t)(V_L\sin\omega t/R_L)d(\omega t)$ *(both transistors)*

$= (V_SV_L/2\pi R_L)\int_0^{\pi}\sin\omega t\,d(\omega t) - (V_L^2/2\pi R_L)\int_0^{\pi}(1 - \cos 2\omega t)d(\omega t)$

$= (V_SV_L/2\pi R_L)(2) - (V_L^2/2\pi R_L)(\pi)$

$\boxed{P_D = V_SV_L/\pi R_L - V_L^2/2R_L}$

With a power supply V_S and a load voltage swing V_L

$$V_{CE} = V_S - (V_S/2 + V_L\sin\omega t) = V_S/2 - V_L\sin\omega t$$

$$I_{EC} = V_L\sin\omega t/R_L$$

and the transistor instantaneous power is given by

$$p_D = (V_S/2 - V_L\sin\omega t) \times V_L\sin\omega t/R_L$$

To find the average power we integrate this expression over the half cycle for which the transistor is conducting.

$$P_D = (1/2\pi)\int_0^{\pi}(V_S/2 - V_L\sin\omega t)(V_L\sin\omega t/R_L)d(\omega t)$$

For the other half cycle the other transistor dissipates the same power, so for the complete output stage the average power dissipation is given by

$$P_D = (1/\pi)\int_0^{\pi}(V_S/2 - V_L\sin\omega t)(V_L\sin\omega t/R_L)d(\omega t)$$

$$= (V_SV_L/2\pi R_L)\int_0^{\pi}\sin\omega t\,d(\omega t) - (V_L^2/2\pi R_L)\int_0^{\pi}(1 - \cos 2\omega t)d(\omega t)$$

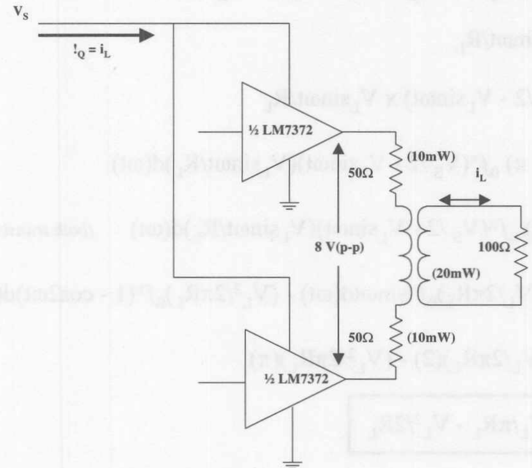
$$= (V_SV_L/2\pi R_L)(2) - (V_L^2/2\pi R_L)(\pi)$$

$$= V_SV_L/\pi R_L - V_L^2/2R_L$$

The second term in the above expression represents the power that is actually delivered to the load.

N.B Taking the second derivative of the expression for power dissipation and equating that to zero will show that the maximum internal power dissipation will occur when the load swing is 63.7% of the supply voltage.

ADSL Load Power Dissipation



National Semiconductor

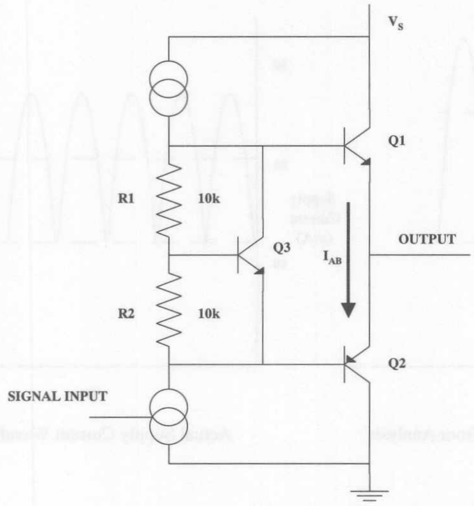
Analog Applications 40

The previous expression is useful for giving a first order approximation to the potential power dissipation in many applications, although it assumes a sine waveform.

Returning to the DSL transmitter, if the average load power is 20mW, V_L is 2V(peak) and substituting this value back into the equation with a 100Ω load gives the average power dissipation for each amplifier as 133mW. With a quiescent power dissipation of 312mW the total package power dissipation has risen to 578mW---- all for a delivered power of 20mW!

Most 8 pin surface mount packages have thermal resistance that is well over 100˚C/Watt. With this level of internal power dissipation, an SO8 package with a θ_{JA} of 140˚C/Watt, at an elevated ambient temperature of 85˚C will have a junction temperature of 165˚C, certainly above the manufacturer's absolute maximum rating. Even though semiconductor manufacturers can offer "thermally enhanced" SO packages, some form of heatsinking is going to be necessary, and this needs consideration in the early pcb development stages. Getting a good idea of what the power dissipation level actually is, means a board can be designed with a healthy safety margin at least cost.

The V_{BE} Multiplier



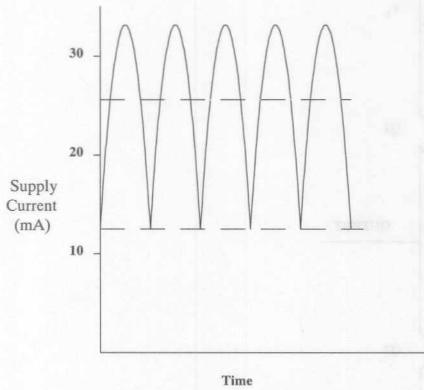
Before moving on to determine the size of heat sink required, let us take another look at that Class B output stage. In the analysis, we assumed that while one transistor was conducting the other transistor was completely off. The transition of conduction from one to the other occurs as the load waveform passes through Vs/2. For the simplified schematic shown, with the bases of both transistors connected together, this would indeed be the case. In fact there would be a dead zone, approximately 1.4V wide (2 base-emitter diode drops), during which neither transistor would be conducting. This gap in the load current causes high levels of cross-over distortion and would be disastrous for most applications.

Cross-over distortion is avoided by using a bias network similar to that shown here. The transistor base emitter diode sets the voltage across R2 to approximately 0.7V. Therefore the current flowing in R2 is 100uA. Except for a small amount of base current, this same current must be flowing in R1, so the collector-base voltage is also 0.7V. This places the total voltage across the transistor at 1.4V, thus compensating for the output stage diode drops.

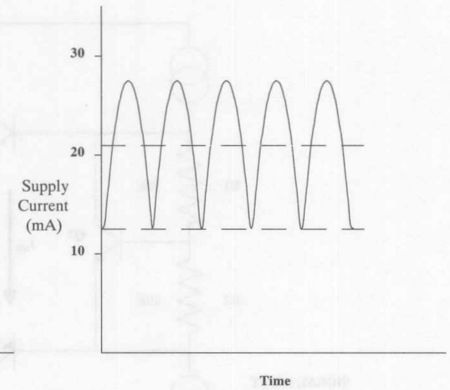
To minimise crossover distortion, the value of R2 is set to give a certain level of current conduction in the output stage even when there is no load current. For the LM7372 the AB bias current is 3.3mA.

The significance of this is that part of the LM7372 quiescent power dissipation comes from this AB bias current. As the output load current increases from zero, this bias current is diverted into the load. Above 3.3mA load current, all of the bias current is appearing as load current. Therefore to assume that the average power dissipation is the sum of the quiescent and load power dissipation is incorrect.

Bias Current added to Load



Supply Current Waveform from Analysis



Actual Supply Current Waveform

The average current for a load power of 20mW is 14.1mA. If we neglect the contribution of the AB bias current to the load current, the total current appears as the peak value of the load current, √2 x 14.1mA or 19.9mA, superimposed on the quiescent current of 6.5mA.

However when we add the AB bias current to the load current, the supply current swing is only 14mA instead of 19.9mA. Now the average value of the supply current is 21mA.

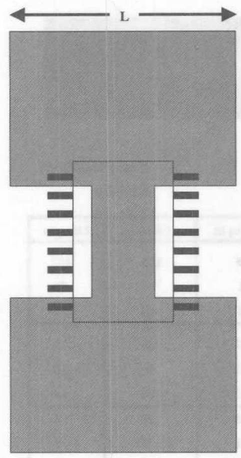
$$P_D = (V_S \text{ X } I_{AVG}) - \text{Power in Load}$$

$$= (24 \text{ x } 21)\text{mW} - 40\text{mW}$$

$$= 464\text{mW}$$

This level of power dissipation in a standard SO8 package would not push the junction temperature above the absolute maximum (barely) at elevated ambient temperatures, but there is no margin to allow for component tolerances or higher than expected signal levels.

SOIC 16 Package



L (in)	H (in)	θ_{JA} ($^{0}C/W$)
1.0	0.5	83
2.0	1.0	70
3.0	1.5	67

National Semiconductor

Analog Applications 43

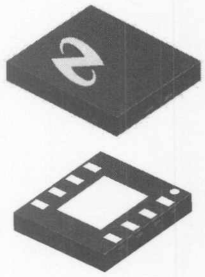
For reasons of reliability, we would like to keep the maximum average junction temperature in the 110˚C to 120˚C range or even lower. With a power dissipation of 464mW and an ambient temperature of 85˚C, this means a total package thermal resistance in the range of 60˚C/W to 80˚C is needed for this application.

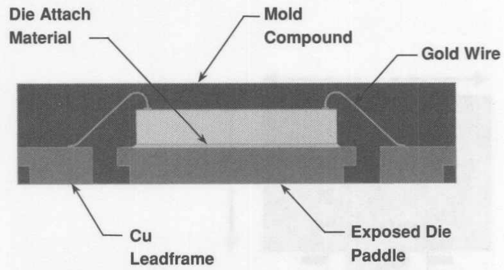
Most Op-Amp surface mount packages, SO8, SO14, SO16 etc have free air thermal resistances much higher than this, but special package variants are available that allow the heat to be removed from the package and dissipated by an area of pcb copper.

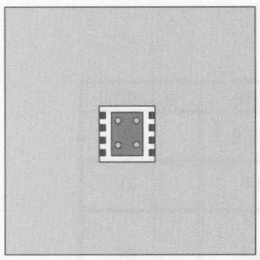
One such package is the SOIC 16. For a dual Op-Amp, only 8 pins are needed, so for the SOIC 16 the end pins of the package are connected to the leadframe. The I/C substrate is attached to the die attach paddle and heat transfers out via these four connections.

Using a "dog bone" area of copper reduces the thermal resistance into the range required. For a θ_{JA} of 70˚C/W a total area of 4 square inches (2600mm^2) of 1 oz copper is sufficient.

LLP Package







Copper Area		0.5 sq in	1.0 sq in	2.0 sq in
Top Layer Only	0.5 oz	115	105	102
	1.0 oz	91	79	72
	2.0 oz	74	60	52
Bottom Layer Only	0.5 oz	102	88	81
	1.0 oz	92	75	65
	2.0 oz	85	66	54
Top and Bottom	0.5 oz	83	70	63
	1.0 oz	71	57	47
	2.0 oz	63	48	37

Thermal Resistance (^{0}C/Watt)

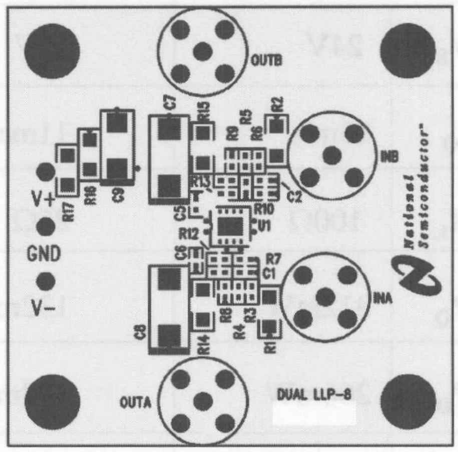
National Semiconductor

Analog Applications 44

A new package from National is the LLP, which has no leads external to the package. This package also has the lower surface of the die attach paddle exposed. Heat from the die flows directly through the paddle to the surface of the pcb. Board copper area used for heat sinking with this package is much more effective as the table above shows. With heat vias to the bottom layer, the same two square inches of 1 oz copper reduces the thermal resistance to 65°C/W. Using the top layer as well, with 2 oz copper, the thermal resistance can be as low as 37°C/W.

With this package, and the previous package, it should be remembered that the copper used for heat sinking will be at some electrical potential. This will be the chip substrate potential which for these technologies will be ground on a single supply, or V- on a split supply. For the SOIC 16 the copper area will be usually on the top or component side. For the LLP8, the use of vias puts the heat sink copper on the bottom or ground plane side, making for an easier layout.

LM7372 Test Board



National Semiconductor Analog Applications 45

Some test boards for the LM7372 in both the SOIC 16 package and the LLP-8 package are available. Shown here is the LLP-8 board populated as a DSL driver. The board can be reconfigured for single ended amplifiers in both inverting and non-inverting gains.

Note that the top copper underneath the package extends out beyond the ends of the package. The two extra vias two the bottom layer at each end are used for added heat sinking if necessary.

LMH6672 Power Dissipation

Symbol	LM7372	LMH6672
V_S	24V	12V
I_Q	13mA	11ma
R_L	100Ω	25Ω
P_Q	312mW	132mW
P_D	266mW	392mW
P_{TOT}	578mW	524mW

National Semiconductor

Analog Applications 46

Since such a large component of the total power dissipation comes from the quiescent supply current, it might be thought that going to a lower power supply for the same current would be an advantage, even though the turns ratio on the transformer reduces the receiver sensitivity. In fact on a 12V supply the LMH6672 draws only 5.5mA per amplifier, so the quiescent component of power dissipation falls to 132mW, less than half that of the LM7372. But now the load is heavier and more current has to be delivered. Calculated the same way as before, the internal power dissipated to deliver power to the load is 392mW, for a package total of 524mW, a savings of only 50mW over the high voltage LM7372. Certainly heat sinking is again required.

New microSMD Devices Since 1999

Micro SMD-4

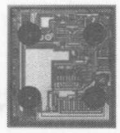
LM20 - Analog Temp Sensor
LM431 - Shunt Reg

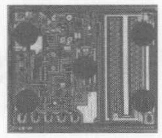
Micro SMD-5

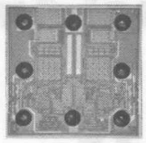
LM74	- Analog Temp Sensor
LP2980	- 50mA LDO
LP2981	- 100mA LDO
LP2982	- 50mA LDO
LP2985	- 150mA LDO
LP3985	- 150mA Low-Noise LDO

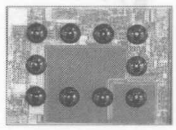
Micro SMD-8

LMC555	- CMOS Timer
LMC6035	- Dual Op Amp
LMC8101	- High Drive Op Amp
LM358	- Dual Op Amp
LM4820	- Fixed Gain 1W Audio Amp
LM4872	- 1W Boomer™
LM4877	- 1W Boomer™ w/ shutdown
LM4878	- 1W Boomer™
LM4890	- 1W Cellular Audio Pwr Amp
LP2967	- Dual 150mA LDO









Micro SMD-9

LM3700/01 – mP Supervisory Circuit Low Line Output
LM3702/03 – with manual reset
LM3704/05 – w/ manual reset and Power Fail Input
LM3706/07 – with Watchdog Timer Output
LM3708/09 – w/ Watchdog Timer Output and Manual Reset
LM3710/11 – w/ Power Fail Input, Low Line Output, Manual Reset and Watchdog Timer
LM3712/13 – w/ Separate Watchdog Timer Output, Power Fail Input and Manual Reset

Micro SMD-10

LM2612	- Programmable,Step-Down DC-DC Converter

National Semiconductor

Analog Applications 47

During our previous seminar series in 1999, we introduced the microSMD package with the world's smallest dual Operational Amplifier, the LMC6035. Since that time we have introduced many more devices in the microSMD package as listed here….and the list continues to grow.

Low Power Consumption

Low Voltage

Operational Amplifiers

Along with all the developments in high speed amplifiers, we have continued to fill in the low voltage, low power consumption operational amplifier functions in our portfolio. This next section will cover some of our activities in LV/LP.

A short historical note:

About 15 years ago the most popular processes for Op Amps were bipolar. Then, as portable equipment became more popular there was a shift to CMOS, and what people called Low Power amplifiers. This was actually meant to signal a need for reduced power consumption and many assumed CMOS would be the process of choice. Although this has happened, ironically it is not because CMOS is inherently low power…that comes about because in digital systems the CMOS transistor is either off (I), with voltage across it but no current drain, or on (0) with current drain but no voltage across it. When a CMOS transistor is used in the analog world, working between fully on or off, it draws as much if not more current than an equivalent bipolar transistor. These early amplifiers really had low performance at low supply current levels. The real gain realised by going to CMOS was a reduction in manufacturing cost (smaller die and less than half the processing steps) and the fact that, with common drain outputs, the CMOS device can be swung almost to the supply rails. CMOS ushered in the era of Rail-to-Rail amplifiers.

New Amplifiers for Low Voltage

- Bipolar
- Low power
- CMOS
- Rail to Rail
- Single Supply

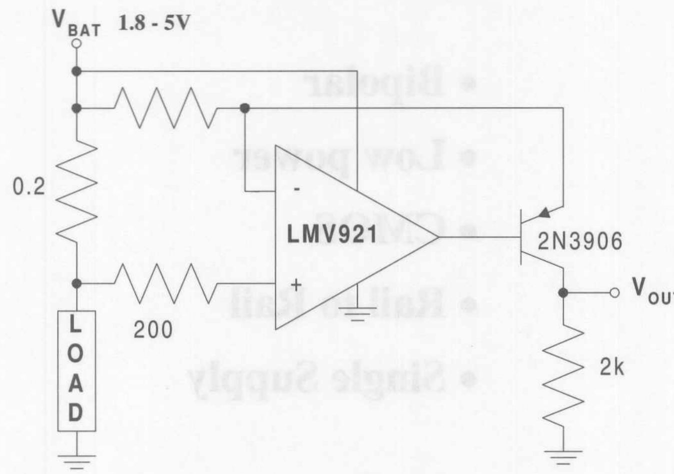
National Semiconductor

Analog Applications 49

Today we are able to offer amplifiers that draw very little supply current, yet have respectable bandwidths and slew rates, using a combination of bipolar and CMOS processes. Rail-to-Rail outputs have become the norm, primarily to ensure good swing capability on on low voltage supplies. Rail-to-Rail capability will depend on the load current, and careful note should be made of the load used for the measurement when comparing amplifiers. Typically, any amplifier whose outputs get within less than 600mV of the rail with a given load, are considered Rail-to-Rail. For light loads, within 10mV of the rails is possible.

Rail-to-Rail inputs are less prevalent than Rail-to-Rail outputs. An amplifier operated in the inverting mode doesn't need common mode range or swing at the input. Many amplifiers are offered as single supply amplifiers, meaning that the inputs can be operated at either of the supply rails but not both. Ground is usually chosen as the reference. Nevertheless, Rail-Rail inputs are being asked for, whether needed or not, and are likely to become a standard feature in low voltage amplifiers. For most amplifiers in this category, the input common mode voltage actually extends beyond the rails, by about 300mV.

Positive Supply Rail Current Sense



National Semiconductor

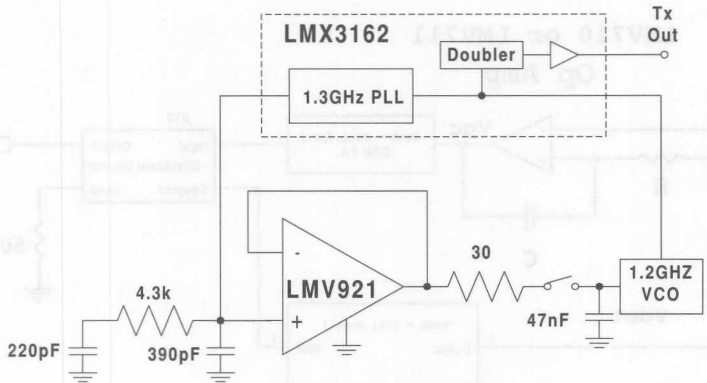
Analog Applications 50

One place where operation at the positive rail proves useful is in current sensing. Nearly any single supply Op Amp could be used for sensing current by the voltage drop across a low valued resistor in series with the ground lead of the load being sensed. However in this arrangement changes in load current will mean there will be changes in the ground potential. If the sense resistor is placed in the power supply lead, then the Op-Amp will be handling input signals at or very close to its own supply voltage.

In this circuit, current flowing through the sense resistor will cause a voltage difference to be applied to the inputs of the Op-Amp. The lower voltage at the non-inverting input will cause the Op-Amp output to pull the base of Q1 low, in turn causing an increased current flow through the upper 200 ohm resistor. The output voltage will stabilise when the current drop in this resistor matches that across the sense resistor. With the values shown, Q1 output will shift by 2 Volts for a 1 Amp shift in load current.

The LMV921 is the single Op-Amp in a 1MHz, RR I/O, 1.8V to 5V supply family, and is available in the SC70-5 package.

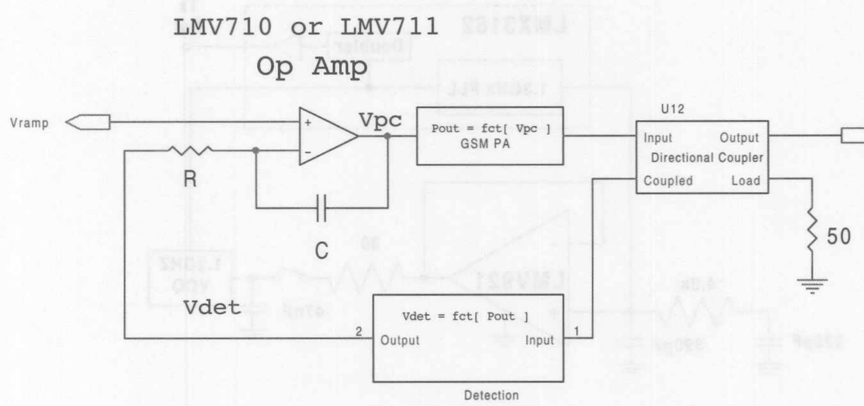
Ultra Low Drift PLL



In the unlicensed ISM band, half-duplex TDMA systems are employed (HomeRF, Bluetooth and Upbanded DECT). Since the data is transmitted and received in different time slots, the same PLL/VCO can be used for modulation and demodulation. Performance is improved by operating in the open loop mode, where the VCO is locked to the desired carrier and the PLL is then shut down during transmission and reception time slots. Particularly in the case of HomeRF, this mode of operation implies that fast lock times are needed, and the drift of the VCO while the PLL is shut down must be acceptably low.

The second order loop filter shown here has a loop bandwidth of 50kHz, giving a lock time of just over 100uS. For low frequency drift when the CMOS switch is open, the VCO has a large 47nF capacitor connected to the control pin. When the switch is closed in order for the PLL to acquire lock, the much smaller size of the required filter capacitance is buffered from the VCO by the LMV921 amplifier.

GSM Power Amplifier Control Loop

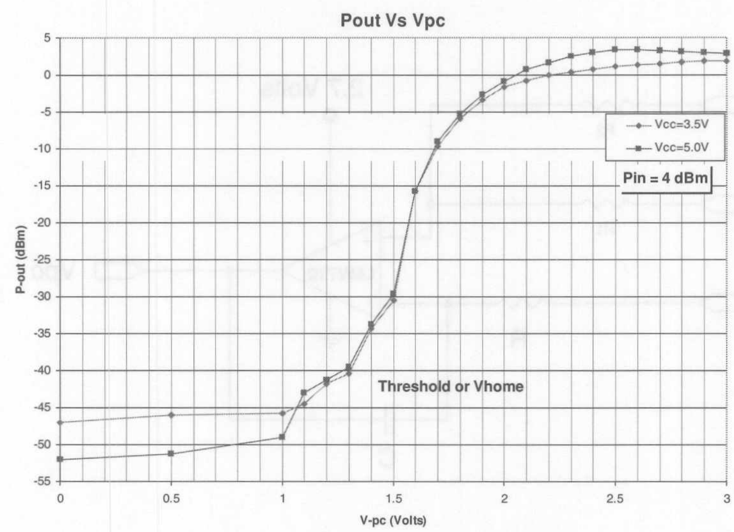


Where low voltage operation at higher speeds is necessary, the LMV710 provides a GBW of 5MHz with a slew rate of 5V/uS. In order to supply the extra speed for stability within a control loop, the LMV710 draws more supply current, 1.2mA, compared to 160uA or less for the LMV921. If overall power consumption is important, the LMV711 in the SOT23-6 package has a shutdown pin which reduces the supply current to 0.2uA in shutdown mode.

In this control loop the Op Amp is used in a differential mode. One input is processing the ramp voltage to set the PA output power level, while the other input is providing a correction voltage for temperature and/or reflected RF power at the antenna caused by temporary mismatching. The amplifier also acts as a filter to prevent high frequency spurs from the controller DAC reaching the PA.

At the output of the PA, a directional coupler is used to feed back the transmitter power level to the controller via an RF diode detector.

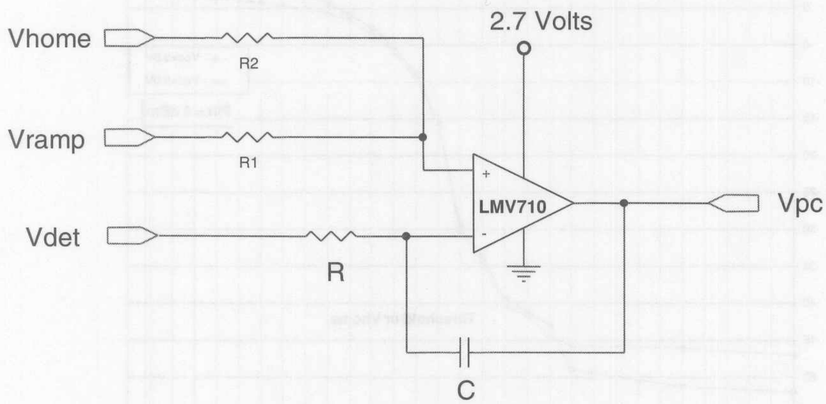
Power Output vs V-pc



National Semiconductor

As the ramp voltage is increased in amplitude, the output power can start out from a very low value with little change until V-pc reaches a threshold level, at which point the power output will go up rapidly with further increases in the V-pc voltage. This threshold value, Vhome, can be preset at the input to the Op-Amp to speed up the turn on time in response to the ramp voltage.

PA Controller with Vhome



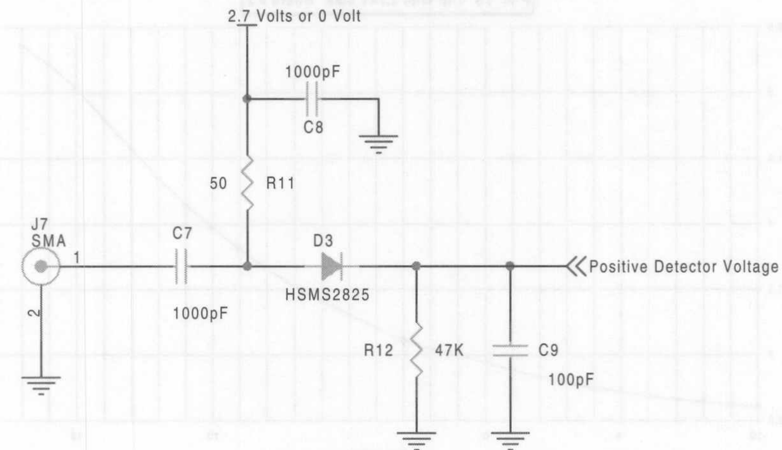
National Semiconductor

Analog Applications 54

Setting Vhome simply requires adding a dc voltage around 1Volt to the non-inverting input of the LMV710.

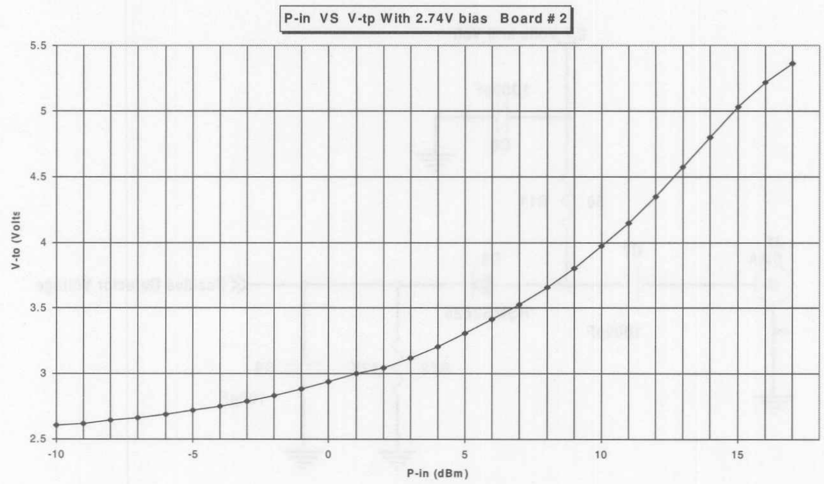
The Vdet correction voltage is obtained from a diode rectification circuit monitoring the rf level from the antenna via a direction coupler. This coupler can take several forms, from a stripline etched in the pcb material, off the shelf SMD components, to wideband resistive dividers or narrow band LC filters.

Positive Detector Rectification



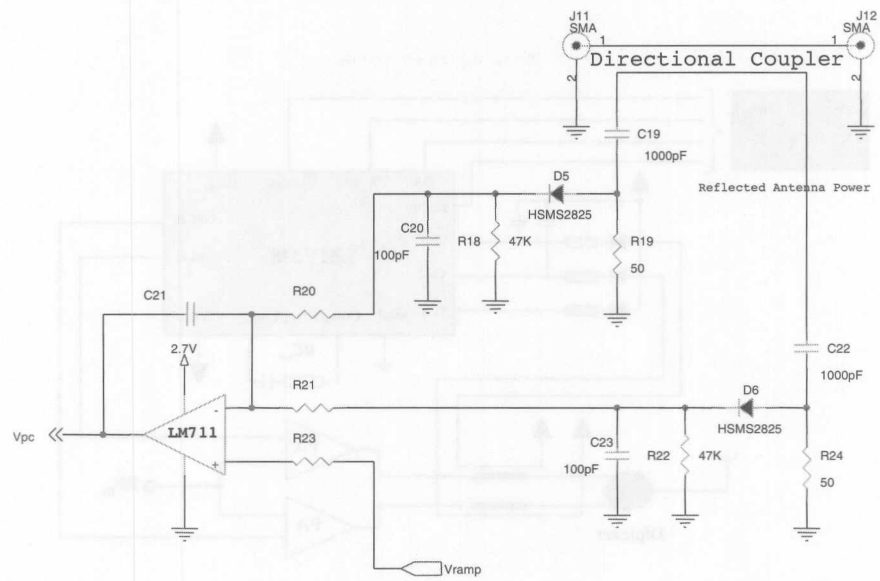
The rectifier circuit shown here uses a diode with the coupler terminating resistor R11 connected to a positive voltage source so that the detected voltage level increases from 2.7V in a positive direction as the power output goes up. If required, with a lower supply voltage for example, the termination resistor R11 can be connected to ground. In either case the diode connection can be reversed to deliver a negative detection voltage.

Detector Voltage vs Power Level



This graphic shows the response of a typical diode circuit with a 2.7Volt bias. If a lower supply voltage means the terminating resistor is connected to ground, then the whole curve becomes level shifted down with only a small change in the overall shape.

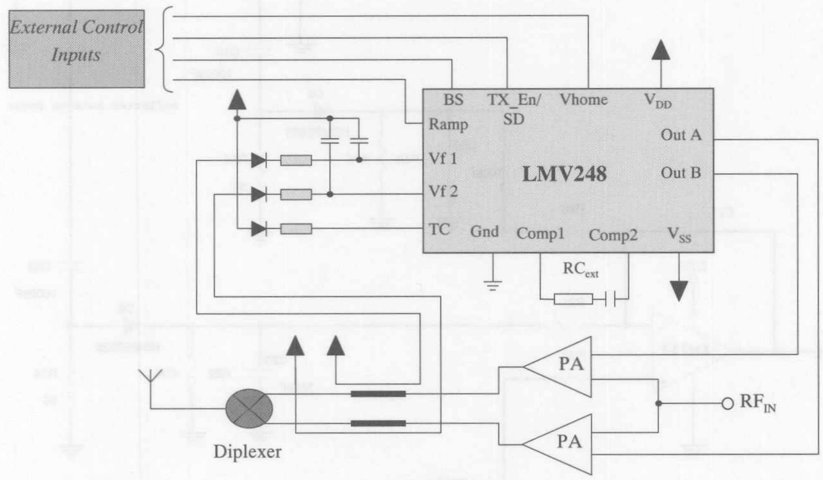
Forward & Reflected Power



National Semiconductor   *Analog Applications* 57

This more complete schematic, using the LM711 includes a second rectifier diode D6. This is designed to protect the PA when the antenna is inadvertently load mismatched.

LMV248 Dual Band Controller

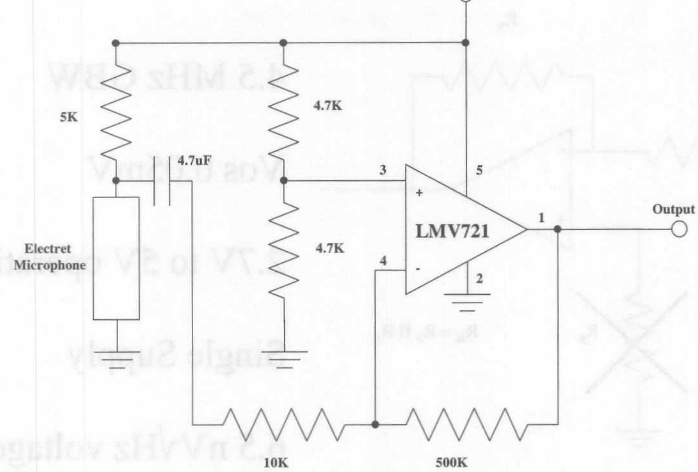


Versatile as they are, just so much can be done with just an Op-Amp. The LM248 is the first in a family of dedicated controllers and, as such, is able to combine many of the desired features into a single I/C.

A band select pin (BS) enables either of the two outputs for GSM or PCN. The ramp and Vhome voltages are applied at two other pins and, as before, a directional coupler is used to feed back the transmitted or reflected power levels to the I/C. There is an additional diode connected in close proximity to the detector diodes in order to provide temperature compensation.

The I/C is able to support GaAs FET, GaAs HBT and bipolar RF power amplifiers with two pins provided for loop compensation. To save power when not transmitting, both output drivers are set to the lowest voltage level. When transmit is enabled, the unused driver is kept at the low voltage state.

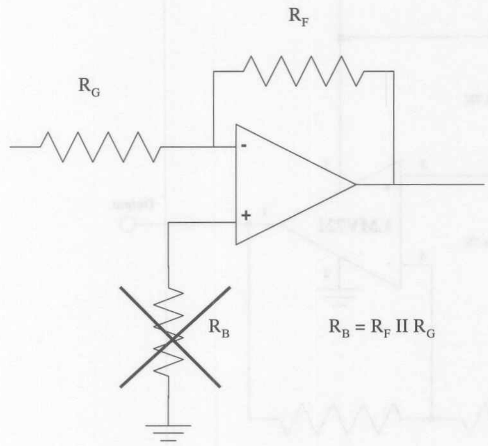
LMV721 Microphone Preamplifier



For yet more speed, where Rail to Rail inputs are not required, the single supply LMV721 single Op-Amp and the LMV722 Dual Op-Amp are available. These amplifiers are able to deliver a 10MHz GBW while drawing barely 1mA of supply current. Along with a noise voltage of less than 10nV√Hz, this wide bandwidth makes the Op-Amp a good candidate for high gain audio applications.

The microphone preamplifier shown here has a closed loop gain of 34dB (50) which means that the closed loop bandwidth will be around 200kHz. This is a factor of 10 higher than the 20Hz to 20KHz audio bandwidth, which will help keep the distortion low. In this inverting gain application the the non inverting input is biased to half the supply voltage, but with some microphone elements a non inverting configuration can be used with the inverting input grounded. This is possible because the LMV721, in common with most single supply amplifiers, has a common mode input that includes ground.

LMV751



4.5 MHz GBW

Vos 0.05mV

2.7V to 5V operation

Single Supply

6.5 nV√Hz voltage noise

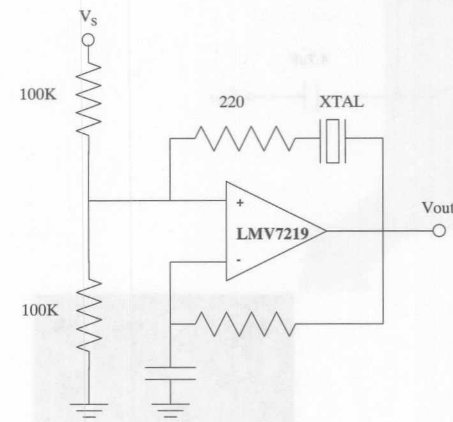
National Semiconductor

Analog Applications 60

Another single supply Op-Amp is the LMV751. The GBW is midway between the general purpose Op-Amps (1MHz) and the high speed LMV721/2 series, and it has been optimised for lower noise, 6.5 nV√Hz, and the ability to drive capacitive loads as high as 1000pF. The LM751 is fabricated on a CMOS process with a bipolar module to provide this drive capability.

While the LMV751 has a low input referred noise voltage, in a given application the external bias and gain setting resistors can be significant contributors to the overall noise performance. It is common practice to match the inverting and non-inverting resistive networks to an Op-Amp. This stems from the bipolar days when input offset currents could contribute to the output offset voltage if these resistances were not matched. The input bias currents of CMOS Op-Amps is very low compared to a bipolar input stage, and the input offset current is correspondingly low, in the case of the LMV751 it is only 0.2pA. This mean that matching the input resistors is not as important and can lead to the complete removal of the non inverting resistor in a single supply application. A further benefit is that the resistor's contribution to output noise voltage is also eliminated.

LMV7219 High Speed Comparator



Tp = 5nS

Tr =1.3nS

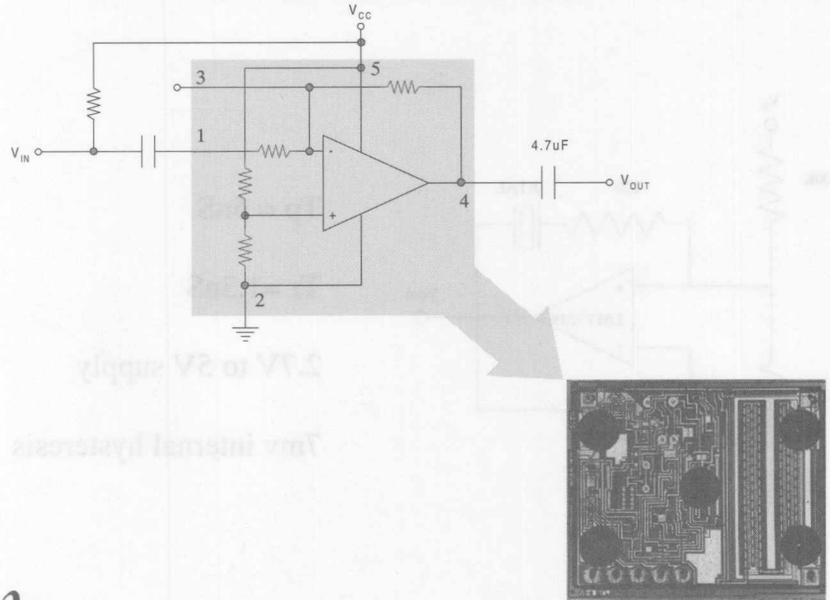
2.7V to 5V supply

7mv internal hysteresis

There is always a temptation to use an available Operational Amplifier as a comparator. While this is more true of quad Op-Amps than the singles (or even the duals) we have been describing, the speed of these devices suggests that they might make reasonably fast comparators operating at the same low supply voltages. This should be approached with caution. For example the bipolar output stage of the LMV751 with a light load will allow the the PNP to saturate, diverting the output current to the previous stage instead of into the load. This causes the supply current to increase to 20-30mA, which could be disastrous. Even when this is not the case, since the Op-Amp is usually compensated for stable operation at unity closed loop gain, the comparator speed will be a lot less than an uncompensated version would be.

A better solution is to look for a comparator able to work on low supply voltages. The LMV7219 is available in SC70-5 or SOT23-5 packages and will work on supply voltages as low as 2.7V. The propagation delay is only 7nS and 7mV of internal hysteresis is built into the switching threshold to avoid oscillations caused by noise on the input when it is close to the switch point.

LMV Integrated Fixed Gain Family



National Semiconductor

Analog Applications 62

Last, but not least, is the LMV1xx fixed gain family.

Because of their intended general purpose use, Op-Amps are surrounded by external components that define the particular function. With surface mount components, these external parts occupy less pcb space than the I/C. Now, with the much smaller packages described earlier, this is no longer the case. Therefore, in large volume applications for a fixed function, it makes sense to bring some of these external components inside the I/C package. Although only very small capacitors can be integrated (< 30pF), resistors up to several hundred kilohms in value are easily included on the I/C die.

Our LMV family includes a number of Op-Amps with outputs biassed to half supply, and inverting gains from -1 to -10.

	DC Gain
LMV101	-1
LMV102	-2
LMV105	-5
LMV110	-10

Another part is the LMV111, which is similar to the LMV321, but has the output biassed to Vcc/2